PRACTICAL INDUSTRIAL FURNACE DESIGN

BY

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IN THE REPRINTING OF THIS BOOK, THE RECOMMENDATIONS OF THE WAR PRODUCTION BOARD HAVE BEEN OBSERVED FOR THE CONSERVATION OF PAPER AND OTHER IMPORTANT WAR MATERIALS. THE CONTENT REMAINS COMPLETE AND UNABRIDGED.

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AFFECTIONATELY DEDICATED

TO

GRACE BOWMAN MAWHINNEY

PREFACE

This book, a revision and enlargement of a series of articles which appeared in *Forging-Stamping-Heat Treating* from December, 1926, to February, 1928, is based upon the belief that the conservation of fuel is of great importance in our modern civilization, and that fuel can be conserved in industrial heating furnaces to a greater extent than it is at present, by a better understanding of furnace operation. The book will have accomplished a great deal if it helps to arouse interest in the further investigation of the waste to be found in the many forms of industrial furnaces, and in the better utilization of the opportunities for this form of research to be had in our industrial plants.

It seems evident that the intelligent interpretation of the observations that can be made of furnace operation in our mills and factories, and the successful application of these observations to the development of more efficient methods, cannot be accomplished without a practical knowledge of operating principles. The laws of heat and temperature distribution and of the many other factors involved in furnace operation are of an abstract nature and are therefore difficult to picture readily in the mind, but, without such a picture, erroneous conclusions are more common than correct results, because of the misleading nature of most thermal phenomena. This book is an attempt to clarify the factors which affect furnace operation.

It is not intended as a theoretical treatise on any phase of the subject; it is simply a discussion of practical methods for the solution of the problems and difficulties most frequently met in the selection, design, and operation of industrial *heating* furnaces as distinguished from *melting* furnaces. The methods are based upon an accumulation of data, observations, and

calculations, and are presented as simply as seems consistent with their value as means for obtaining practical results. All of them have been used with repeated success by the author, although he believes that there is room for great improvement in furnace theory and hopes to be one of those to continue the development of methods for the more exact solution of these problems. Present knowledge of the subject is surprisingly indefinite, but what is known must be more generally understood before more exact data will be developed or applied in practice.

The pioneer American book on the subject of furnace design is *Industrial Furnaces*, by Professor W. Trinks, who, as head of the Mechanical Engineering Department of the Carnegie Institute of Technology, taught the author the fundamentals of the subject. That volume contributed a great store of information on the theory of furnaces, and, in order to avoid repetition of data contained therein, the reader is referred in several instances to that work for the derivation of some of the theory which has been used in this book.

The author desires to record here his deep appreciation of the personal interest and assistance which Professor Trinks has given him. He is also indebted to Mr. J. D. Keller and to Mr. Horace Drever for their assistance in criticizing parts of the text, and to Mr. D. W. Kent for his cooperation during the writing of the book. Finally, thanks are due to the many commercial companies which have supplied information and illustrations.

MATTHEW H. MAWHINNEY.

BRYN MAWR,
April, 1928.

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PRACTICAL INDUSTRIAL FURNACE DESIGN

CHAPTER I

INTRODUCTION

ALTHOUGH the industrial use of metals is comparatively new, the art of treating metals is very old and history contains many references to craftsmen in this art; little mention, however, can be found of the tools which they used. The same thing is largely true to-day, in that, although few will dispute the statement that metals constitute one of the principal foundations of modern society, the average person knows little of the methods or equipment used in their manufacture. Manufacturers whose business is built up around the use of metals, especially iron and steel, are particular in obtaining certain definite properties in the steel they buy, but often do not understand how these properties are obtained; and metallurgists, whose business it is to produce these properties in iron and steel, are frequently hazy about the operating principles of the furnaces used to produce them. In view of the rapid strides that have been made in the science of metallurgy to produce steels suitable for the infinite variety of modern requirements, it is surprising how little is definitely known about the theory of the furnace equipment required.

Probably the chief reason for the lack of general knowledge of this subject is the lingering idea that there is little to know—that a furnace is simply a brick chamber to which heat is applied, and that a good bricklayer is a furnace engineer. This situation did prevail for many years, but the development of new materials for construction and a growing demand for accuracy and economy are gradually changing this notion. The indus-

trial furnace is becoming too important to be neglected and must soon be accepted as a scientific precision tool.

Before considering the various details of furnace design and construction, it is interesting and logical to look back briefly at the history of metal working to see what rôle the industrial furnace has played. Such a review will make it easier to understand the causes leading up to the present importance of the industrial furnace and the position of modern furnace equipment in metallurgical work.

All reviews of the history of iron commence with the Biblical reference to Tubal Cain as an artificer in brass and iron. The account of the wanderings of Moses and many other references in the Bible also mention the use of iron. Herodotus stated that iron was employed by the Egyptians in the construction of the pyramids three thousand years ago; and Homer, who is supposed to have written the Odyssey about 850 B.C., showed a knowledge of the tempering and heat treatment of steel in describing the death of one-eyed Polyphemus at the hands of Ulysses, and in mentioning incidents at the siege of Troy. Steel is known to have been made in small quantities in India when that country was conquered by Alexander in 320 B.C.; and the Persians and Syrians were also steel makers, Damascus in Syria having already become famous for its swords. Spain made iron in ancient times and, with the encouragement of the Romans who conquered her in 194 B.C., flourished for hundreds of years in the business.

The processess used in these very early times for making iron and steel were simple, and the quantities produced were small. The steel produced in India and Syria was made in small crucibles with charcoal, and the early iron was made in holes dug in the ground, air for combustion being obtained either by natural draft on windy days or by means of crude bellows of goatskin. Most of the metal was used in making weapons, and even for that purpose its use was not common until about the tenth century, when the Catalan bloomary (from the Anglo-Saxon word *bloma*, meaning *lump*) was devised for making lumps of malleable iron directly from the ore at Catalonia in Spain.

These bloomaries, a form of which is shown in Fig. 1, were usually built in a hillside for the convenient charging of ore, limestone flux, and charcoal, and were lined with clay or bricks capable of withstanding the high temperature. The lump of iron obtained was hammered into the desired form by expert artisans.

Progress in iron making, from this time until the discovery of methods of making steel in large quantities, was very slow. The metal used was practically all malleable iron in lump form,

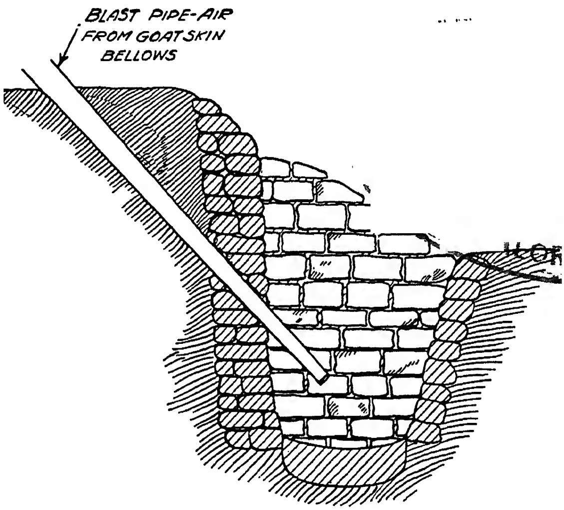


FIG. 1.—Section through Early Catalan Forge.

and although cast iron was known it was apparently not used until the fourteenth century, when the Germans, Belgians, and French in Central Europe developed the first blast furnaces for making castings. This development probably resulted from the fact that as the bloomaries for directly producing iron became larger it became increasingly difficult to prevent the formation of cast iron during operation. The process evolved in Central Europe during the fourteenth and fifteenth centuries consisted in making cast iron in pigs in the blast furnace, reheating it in a forge similar to the Catalan bloomary to produce wrought iron, and hammering the resulting metal into shape.

Castings were also produced without this working, the first cast-iron stove having been made about 1490 in Alsace. Wooden bellows, invented by Hans Lobsinger, an organist of Saxony, were used with blast furnaces in Germany in 1630, but did not entirely replace the original leather bellows for many years.

Having been developed in Central Europe, the blast furnace was introduced into England in the fifteenth century. Small cannons were used in 1346 at the battle of Cressy, and larger ones, weighing two and three tons, were made possible by the use of castings in the sixteenth century, but progress was not rapid. The next important development in iron manufacture, which took place in England and was due to a threatened shortage of wood for charcoal in that country, was the introduction of coal for furnace fuel. Dud Dudley is credited with this development in 1600, but it was some time later before it became practical. The invention of the cylindrical cast-iron bellows by John Smeaton in 1760 and improvements in the steam engine by James Watt in 1769 prepared the way for the construction, at the Carron Iron Works in England, of a blast furnace that quite closely approximated the present modern furnace, such as that shown in the foreground of Fig. 2.

The next great impetus came with the invention of practicable methods for rolling iron with grooved rolls, in 1783, and of the puddling process, in 1784. Both inventions were made by Henry Cort and established Great Britain as the leading iron manufacturing nation for many years. The use of rolling made possible the quick manufacture of many metal forms formerly wrought tediously by hand, and the puddling process made it possible to control the process of making iron so as to obtain a very high-grade product. This process consists of melting pig iron from the blast furnace in a puddling furnace and adding to the liquid iron a quantity of limestone or other material to absorb phosphorus and sulphur. These impurities are drawn off in the form of slag, and the process continued until the bath of pure iron becomes thick and spongy, when it is worked by puddling into balls and withdrawn from the fur-

nace to be squeezed into blooms. Figure 3 shows a puddling furnace in operation.

In the meantime, the infant American colonies were beginning the manufacture of iron. The first iron was made at the

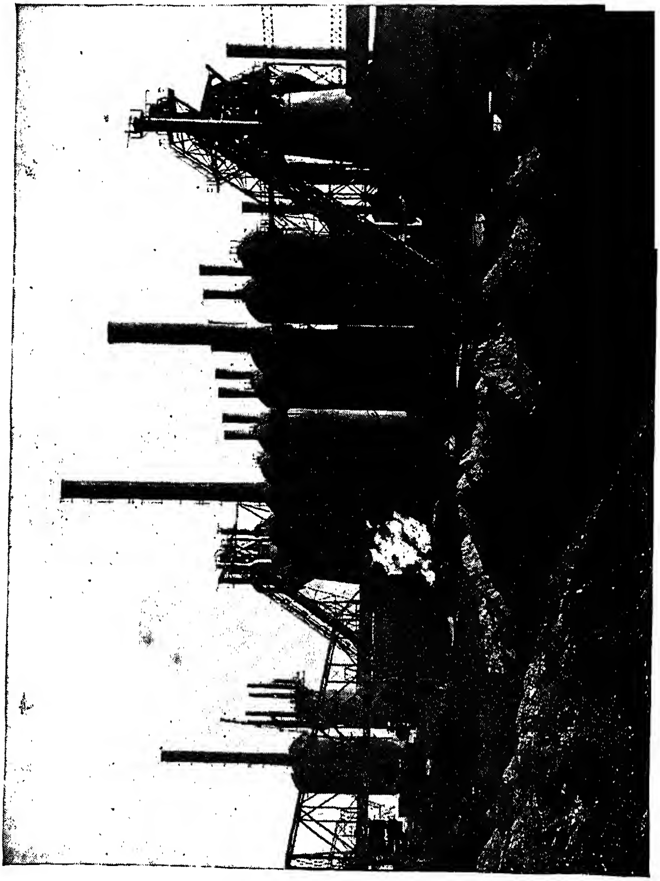


FIG. 2.—Blast Furnaces and Stoves.

Massachusetts Bay Colony in 1645 in a blast furnace and refinery forge, and Massachusetts remained the leading iron colony for a hundred years. In 1716 Thomas Rutter built the first bloomary forge (near Pottstown) in Pennsylvania, called the Pool Forge, and having an output of 28 tons per week. By 1750

Pennsylvania had taken its place as the leading iron-making state in the colonies. Wood being plentiful, charcoal was used in all the early American forges, and coal was not introduced as fuel in America until 1830, when anthracite was first used, to be followed by bituminous coal in 1840. The first rolling and puddling mills in America were built about 1817.

This brings us to the beginning of the nineteenth century and the dawn of the age of steel. Up to that time, practically

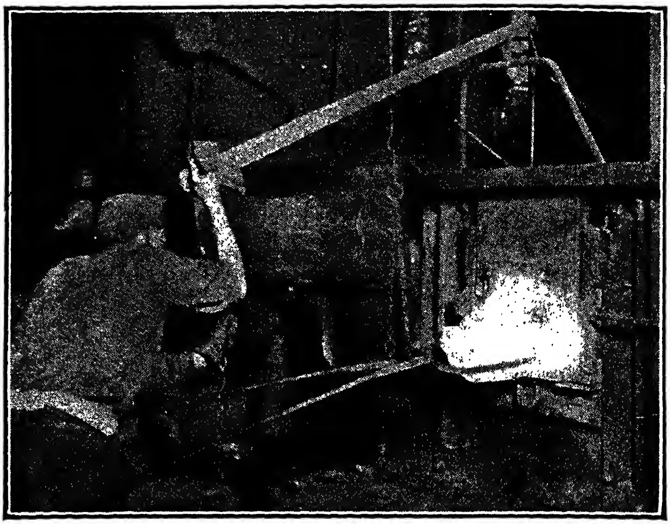


Fig. 3.—Drawing the Ball from a Puddling Furnace.

the only fuel in use was charcoal, and the furnace business, as such, was unknown. It would seem that the realization of this should be of decided interest to anyone interested in the world's progress. In view of the fact that up to about 125 years ago the world had practically stood still industrially through all the centuries of its known existence, does it not seem that our present tremendous industrial pressure may be a mere "flash in the pan" or temporary experiment, rather than an established order of things? And does it not appear logical to believe that the ultimate success of this experiment may depend on our intelligent conservation of the world's resources?

Progress during the first half of the nineteenth century consisted chiefly in improvements in cast-iron and puddling practices and developments in rolling and forming processes. James Neilson invented the use of hot-blast air in blast furnaces in Scotland, in 1828, greatly increasing the yield and efficiency (battery of modern stoves for heating blast shown in Fig. 2); and waste-heat boilers were first used in 1846, in America. In 1815 William Murdock used gun barrels in Scotland to conduct coal gas for street lighting and created a great demand for gas pipe, which stimulated the development of tube making. Iron ships were successfully tried out in 1818 and caused a demand for iron plates. Rails, weighing 20 pounds per foot, and of H section at that time, were beginning to be needed in quantities in 1840, as Peter Cooper's first locomotive, *Tom Thumb*, of the Baltimore and Ohio lines, had been so successful at Baltimore in 1830. Helve and tilt hammers were the first forerunners of modern forging practice. These were closely followed by the single-acting steam hammer, invented by James Nasmythe in 1842, and then by the double-acting hammer for shingling puddled bars and for making iron forgings from these bars. This machinery, as it gradually grew in size (Fig. 4 shows the size of a very modern press) to take care of the larger forgings, demanded by the growing industry, in itself demanded heavier and stronger parts. The resulting industrial pressure led, in the middle of the century, to the discovery of methods for making steel in large quantities.

Crucible steel in quantities was first made by Benjamin Huntsman in 1750, but in 1810 only 917 tons of this steel was made in America, indicating its limited use. No easy process for making steel in large quantities was devised before the invention of the Bessemer process in 1856 and the Siemens open-hearth process in 1861. In the Bessemer process (a Bessemer converter is shown in Fig. 5) the impurities are removed from iron by blowing air under high pressure through the liquid iron charged in the swinging converter. The impurities are oxidized and go off in the form of gases, and heat is maintained in the molten metal by this chemical action.

Each heat requires only twenty to thirty minutes, and several tons are charged at a time. The open-hearth process (Fig.

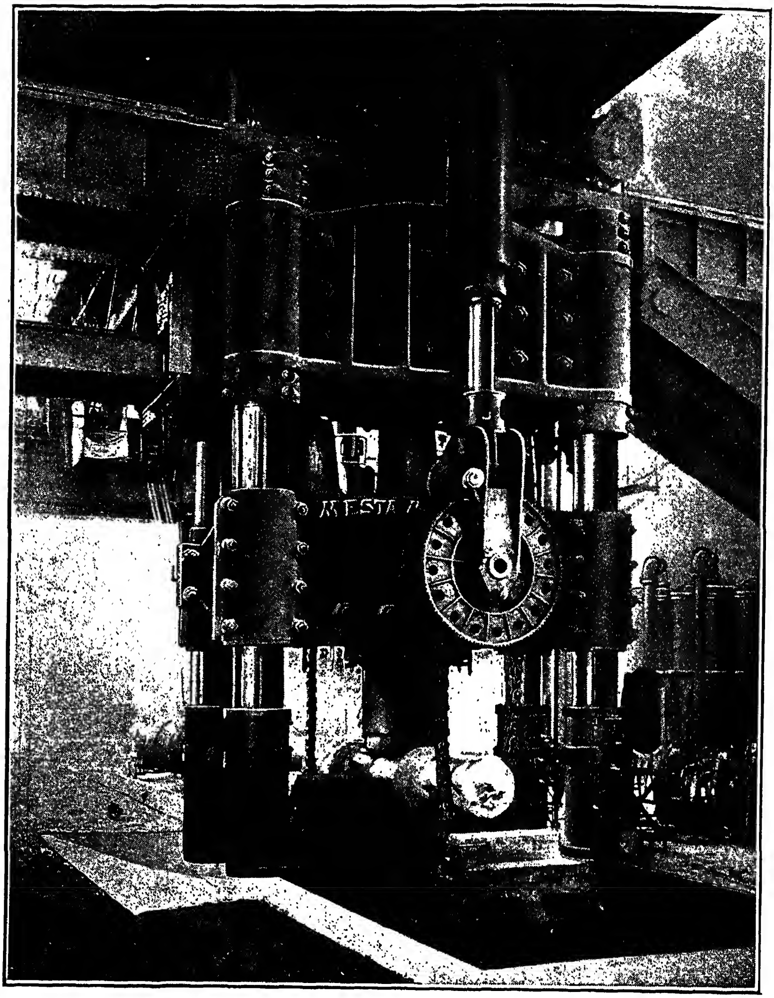


Fig. 4.—A 14,000-ton Forging Press.

6 shows a view of an open-hearth furnace) consists in melting impure iron by the application of external heat, removin impurities by slagging off with limestone flux, and addin

or other alloys to produce steel of the desired analysis. The process requires eight to twelve hours, but furnaces with a capacity of 100 tons are extremely common.

These were discoveries of tremendous importance, because they made possible the quantity production of steel, whose prop-

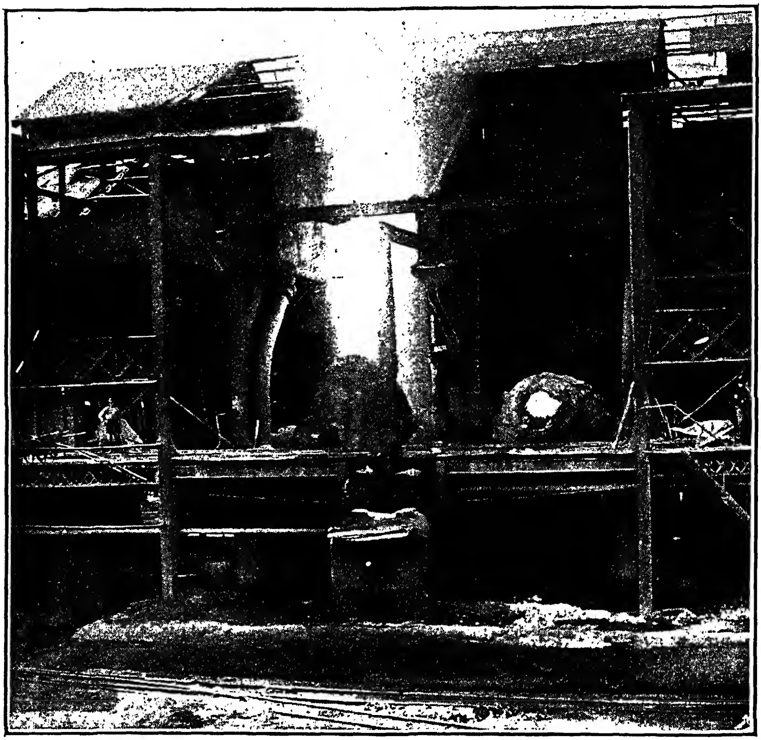


FIG. 5.—Bessemer Converters.

erties may be varied by treatment to suit various conditions required, in place of iron which lacks these variable characteristics. Ordinary steel is purified iron to which carbon has been added in varying quantities to produce various properties, and these discoveries form the basis upon which rests the entire science of modern metallurgy, and consequently the industrial business of to-day. Very high-grade tool steels are

still made by the crucible process from old-fashioned puddled iron, but, except for these limited varieties, the puddling process has been superseded and steel is made by the cheaper and more rapid Bessemer or open-hearth processes.

Rapidly reviewing the fuel situation during the nineteenth century, we find that, up to the middle of the century, hard coal was still the chief fuel, with bituminous coal as its only competitor. In 1847 natural gas was used for metallurgical

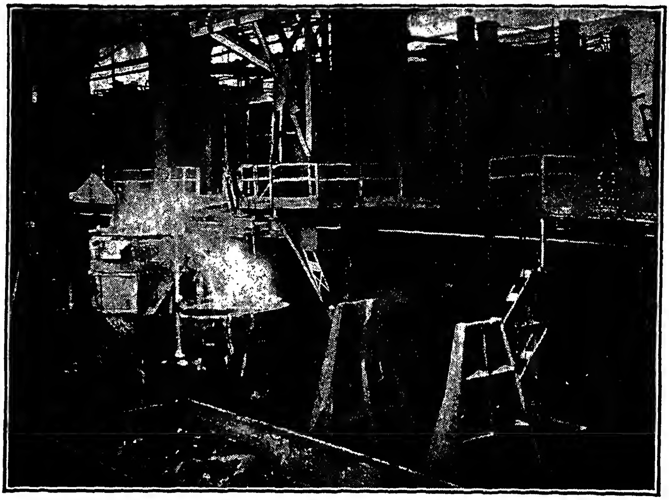


FIG. 6.—An Open-hearth Furnace-Tapping Side.

purposes in Pennsylvania, Ohio, and West Virginia, and held an important position in these states for the remainder of the century. In 1859 the first oil well was drilled by Drake at Titusville, Pa. It is interesting to note that this well was 70 ft. deep, with a production of 20 barrels a day, as compared with an average depth of 3300 ft. in the Texas field in 1920, with an average production of 1500 barrels in twenty-four hours per well. Oil was not used industrially to any great extent until 1870, and not very much then until it was applied to reheating furnaces after the advent of steel. Producer gas was extending very slowly into the largest works in 1890, but its progress

was slow because it required new furnaces and there was not sufficient economic pressure to warrant the change. Coal was used almost exclusively when the century closed, and all other fuels did not comprise over 10 per cent of the total energy used.

The invention of steel processes immediately created the necessity for furnaces to reheat the steel for rolling and forging into shapes and for annealing to remove working strains. The first of these furnaces were of the simplest kind, although sometimes built with regenerators owing to the influence of the design of Siemens' open-hearth steel-making furnace, which by 1880 was very well known. They were all large and strongly built, and the fact that many of them are still in operation is testimony to their ruggedness. The idea of a continuous furnace for steel mill rolling, where the material passes continuously through the furnace and is preheated by waste gases before reaching the hot zone of the furnace, was first originated by Eckman, of Sweden. Skid rails and mechanical charging were added by Allen, of Sheffield, England, and still further improvements were made by Morgan, of Worcester, Mass., just at the end of the nineteenth century. The close of this period, then, finds only a few types of furnaces in existence, all designed for heavy reheating work, and fired almost exclusively by coal on the grate.

The dawn of the twentieth century announced the arrival of a busy day for the steel craftsman. Suddenly, great strides were being made in the building of engines, automobiles, and railroads, in shipbuilding, structural steelwork, and electrical machinery; and the metallurgist was hard pressed to produce the right steels for the demands which were becoming almost infinite. Most of the progress was made possible by the discovery of various alloys, including tungsten, vanadium, chromium, etc., and by the invention of new methods of heat treating. Carburizing, case hardening, tempering, quenching, sherardizing, and other methods were devised, and each one required better control of temperature and furnace atmosphere. Furnace companies sprang up to help supply the metallurgist with equipment to do this work, and because fuel was still plentiful and

cheap, and everyone so busy, little thought was given to the most efficient methods of heating or the best manner of obtaining accurate results. The World War added a great impetus to the discoveries of new methods of heat treating and industrial heating. Money was spent freely to try out any method that might produce results, and there were many failures; but each failure added to the experience of engineers engaged in this work. Experiments were made which under ordinary conditions would have required a much longer time, so that, from the standpoint of conservation of fuel resources, the War was of some advantage. When the War ended, science and metallurgy had pretty well caught up with the demands of the industry and had time to catch their breath and analyze and catalogue their discoveries for guidance in future practice. The American Society for Steel Treating was formed in 1919 and has functioned well in supplying the inspiration and means for doing such work, recording metallurgical data in permanent form, and sponsoring further research and investigation. But there has been comparatively little attempt to study or record the experience and knowledge applying to the industrial furnace itself, with the result that, although furnace design has advanced in step with the demands for better equipment, there are few actual, definite data available, and antiquated furnaces are still used in many industries with consequent wastes of fuel.

Having reviewed the historical background leading up to the present status of the heating furnace as an industrial tool, let us now briefly outline the various questions arising in the selection and design of an industrial heating furnace, in the order in which they are generally met in practice and in which they will be considered in this book. The problems herein considered apply only to the various furnaces used in heating metals to temperatures below the melting point.

OUTLINE OF PROBLEMS TO BE CONSIDERED

Selection of Fuel.—One of the first decisions which must be made by the management of any industrial plant requiring a

furnace is the selection of the fuel to be used in firing the furnace. This is a matter of greatly increasing importance. We have seen in preceding paragraphs that at the beginning of this century the only fuel in use was coal, but the last comparatively brief period of twenty-eight years has seen a great change in this condition. In steel-mill furnaces, producer gas, made from coal, has attained very common use; its natural advantages and the improvements being made in the United States and abroad —where the necessity for conservation is realized before it is in this country—appear to insure its continued importance as an industrial fuel. Fuel oil has an extremely general use and will undoubtedly continue to be important, although fear for the future supply and the increasing use of crude oil for other purposes is having a noticeable affect on the selection of this fuel for new furnaces. By-product tar and coke-oven gas are cheap and valuable fuels wherever modern by-product ovens are used for the making of coke, and are so common to-day that, together with producer gas and fuel oil, they have almost entirely replaced the use of coal on the grate for reheating furnaces. However, the continued improvements in the application of stokers to industrial furnaces, with their possibilities of utilizing poor grades of coal with reasonable labor costs, are now restoring coal to much more general favor. For forging, annealing, and heat-treating furnaces, coal on the grate and producer gas are seldom used, and tar or coke-oven gas are not frequently available, so that the choice is now generally between artificial gas, oil, or electricity, with stoker-fired or powdered coal sometimes advantageous. The electric furnace attained tremendous importance during the recent war, and although the expense it involves has to some extent retarded its development, the very great advantages that it possesses under some conditions have easily maintained it in a position of importance.

The question of the proper fuel depends on a number of factors, including cost, relative advantages, requirements of the particular process under consideration, geographical location and availability, and the future supply.

Selection of Furnace Type.—After the fuel has been selected, the next step is generally to determine the method by which it is to be applied and the method of heating required by the process under consideration. This requires a knowledge of the factors to be considered in choosing between the various types of furnace, such as continuous, batch-type, overfired, underfired, direct-fired, and sidefired furnaces, as well as a knowledge of the methods which have been found to be best for the more standardized heating processes. Next comes the question of furnace size, which depends on the size, quantity, and regularity of supply of the work to be heated. The correct determination of size has a decidedly important bearing on the fuel economy of the furnace in operation. There are many furnaces which are consuming more than a reasonable amount of heat energy because they were designed to take care of possible future increase in production, when a battery of smaller units, installed as required, would have been the efficient and economical arrangement. There can be such a vast difference between the efficiency and satisfaction of operation of the right and wrong type and size of furnace for any heating operation that the importance of these decisions in the installation of a furnace cannot be exaggerated.

Methods of Material Handling.—The growing importance of labor saving in industry has had its effect on the design of industrial furnaces, and most profitable improvements have been accomplished in the way of continuous methods of handling heated work through the furnace and simplified ways of conveying material to and from the furnace. The question is almost entirely one of dollars and cents; and the saving which accompanies these improvements is seldom a clear profit, because the continuous or automatic equipment is usually more complicated, with higher first cost and increased cost of upkeep. The amount of this additional expense is greater for industrial furnaces than for almost any other type of equipment, on account of the temperature factor. The result is that a considerable number of installations are made which require little handling labor and are good examples of mechanical operation and achievements in

design, but which are operated at a greater overall expense than would be the case with cruder methods.

Fuel Consumption of Furnaces.—The amount of consideration which is being given to this phase of the question of industrial-furnace design is constantly increasing for reasons previously outlined, and its importance will unquestionably increase with increasing shortage of various fuels. The need for economies in industrial fuels has long been felt in European countries and has resulted in many devices for economy which have not found favor here because fuel prices did not warrant the additional expenditure involved, but all indications are pointing to a day in the near future when the conservation of fuel will be a question of general interest and importance. In the meantime, valuable energy is constantly wasted, and it is to be regretted that measures of this sort must be delayed by financial policy until actual shortage forcefully demands their acceptance. That there is some realization of this at the present time is indicated by the increasing importance of fuel consumption among the talking points used in sales competition. The data available for the determination of such guarantees are still insufficient, however, as witnessed by the wide variation in published figures.

Materials of Furnace Construction.—The greatest changes in furnace design in recent years resulted from the amazing development of high-temperature alloys. As late as 1923 the idea of high-temperature metals was new and their cost was entirely too great to allow any practical use of them in furnace construction, so that cast iron and cast steel, with their limited life and strength, were the only metals used to any extent. This kept the design of furnaces necessarily plain and crude unless very complicated and unsatisfactory water-cooled parts were used; but the commercial development of heat-resisting metals has opened up vast new fields to the furnace engineer in the possibilities for continuous handling of material through furnaces, and has done much to remove the old-fashioned bricklayer from eligibility to the title of furnace engineer. The uses of this form of material are endless, but its development has necessarily been somewhat retarded by failures due to incorrect application.

The advances which have been made in the manufacture of refractories have also been remarkable, and the physical properties and proper use of this broad range of materials are worthy of detailed discussion.

Automatic Heating Control.—One chapter of this book is devoted to the beneficial effect of the automatic control of heat energy on the amount of fuel required and on the quality of the heated product. A description is given of the different types of apparatus which have been developed for this purpose.

CHAPTER II

SELECTION OF FUELS

The selection of the most suitable fuel for various kinds of heating is important in the conservation of this valuable national asset. As previously mentioned, the older countries of Europe, not so liberally supplied with natural fuels, have for many years felt the economic necessity for conservation; and in economical utilization of heat energy they have advanced beyond the United States, where fuel has always been so plentiful and cheap that efforts at conservation have meant financial loss. The same necessity is beginning to be felt in this country, however, and steps are gradually being taken to remedy the condition. The question probably first came to our national attention during the late war, on account of fuel shortages for power purposes, resulting from confusion and sudden demands which were made at that time. The Fuel Engineering Division, which was formed in the United States Fuel Administration in Washington, under its Bureau of Conservation, has functioned well in the conservation of fuel in power plants and on the railroads, but does not seem to have devoted much attention to the processes of industrial heating, where enormous wastes still occur.

Since the time is approaching when the desirability of saving will be increased by financial necessity, which is essential for any real progress in this line, and because the use of the proper fuel in the proper place is a big consideration, a study of the various fuels available is highly desirable. Since there are many excellent books devoted to fuels in general, and each heating process presents a separate problem, we shall confine our attention to the most important phases of the selection of the best form of heat energy for any heating process. The following are the principal factors to be considered:

Comparative nature of fuels: properties, preparation, firing, and advantages.
Comparative costs of fuels: preparation and overall costs.

Before considering these items in more detail, let us briefly outline the principles upon which the theory of combustion rests. In the first place, the process of combustion is the same for all fuels, to the extent that it is always the oxidation by chemical action of the combustible content of the fuel to produce heat energy at high temperatures, the theoretical amount of heat energy depending upon the calorific power of the fuel and the theoretical temperature depending upon the constituents of the fuel. The combustible contents, usually carbon and hydrogen or combinations containing these elements, are combined with the oxygen of the air, supplied in the required quantity, to produce combustible products of combustion, inert gaseous products of the fuel and the air, and solid substances which remain in the form of ash.

In perfect combustion (when every particle of combustible in the fuel is completely burned and every particle of oxygen supplied is utilized) there are no combustible products. However, as actual combustion is seldom perfect, because of the incomplete mixture of air and fuel, some unburned carbon monoxide gas is always found in the flue gases if the amount of combustion air is too small or if the mixture is poor. If an excess of air is supplied to insure complete burning of all particles of fuel, the inert products are affected. In perfect combustion the inert products are carbon dioxide from combustion of carbon in the fuel, nitrogen from the air and fuel, and water vapor from combustion of the hydrogen in the fuel. With an excess of air, oxygen also appears in the flue gases.

There is a definite relation between the oxygen, carbon monoxide, and carbon dioxide contents of flue gases, which has been explained by Professor W. Trinks in his *Industrial Furnaces*, Vol. I, page 96. Figure 7 is an Ostwald chart for fuel oil, which the author has calculated to amplify the series of such charts which is given in Professor Trinks' book to show this relation for

different fuels. Such charts are useful in checking the accuracy of Orsat analyses of flue gases, and in calculating, from such an analysis, the excess or deficiency of air existing in a furnace, the method being explained by Professor Trinks. Ash is produced in the combustion of solid fuels, in addition to gaseous products, and is largely composed of inert material, although combustible carbon usually escapes the action of the air and appears in the ash in varying quantities, depending upon the efficiency of firing.

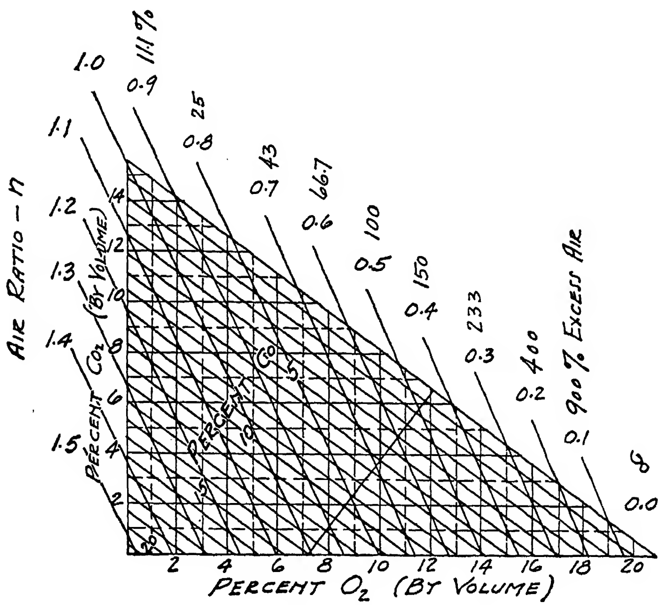


FIG. 7.—Ostwald Chart for Fuel Oil.

The calorific power of fuel (inherent chemical heat content) is called either *higher heating value* or *lower heating value*, depending upon whether the latent heat of water vapor in the flue gases has been subtracted from the calorific value of the fuel. The flame temperature of burning fuels depends upon the heat liberated in combustion and the heat-absorbing capacity of the flue gases. If the flue gases produced are dense and consequently of large heat capacity, or if they contain much excess air, the flame temperature will be low. So-called lean fuels, such as

blast-furnace gas, burn with comparatively low-flame temperature because they are both low in calorific power and high in inert flue gases when burned. Practical calculations of necessary combustion values are considered further in Chapter V on fuel consumption.

With this brief introduction, let us see what fuels are available, considering only those which have an industrial application to heating furnaces, and taking up the factors to be studied in the order named at the beginning of this chapter.

Comparative Nature of Fuels

Fuels used for industrial furnaces include the following:

Solid fuels: Bituminous coal, coke, and lignite.
Liquid fuels: Fuel oil and tar.
Gaseous fuels: Natural gas, coal gas, water gas, oil gas, producer gas, blast-furnace gas, and coke-oven gas.
Electricity.

The points to be considered for each of these fuels can be conveniently divided into the following headings: physical and chemical properties; preparation for burning; methods of firing; and discussion of suitability for different conditions.

Solid Fuels.—For industrial heating, solid fuels consist largely of bituminous coal in the many varying forms in which it occurs in different parts of the country. Present coal production is limited chiefly to anthracite and bituminous coals. Anthracite coal is best suited for domestic use, railroad, and steaming purposes on account of the small amount of smoke which it produces, and is never used for industrial-heating furnaces. Of 80 million tons mined in 1917, for example, 51 millions were used for domestic purposes and the remainder for railroads, steaming, and export. Of 366 million tons of bituminous coal mined in the same year, 57 millions were used domestically, while 176 million tons were used industrially, and the remainder was utilized by electric utilities, coke ovens, and manufactured-gas plants. The coals used for industrial purposes can be classified as cannel coal, semi-bituminous, bituminous, sub-bituminous,

and lignite, and are produced by the different geological conditions prevailing during their formation. In general, coal is the result of the decay of an abundant accumulation of plant growth in prehistoric ages. This decayed material (peat) has been gradually devolatilized and otherwise changed by the chemical action caused by pressure exerted by movements of the earth's crust.[1] Variation in the type of vegetation, extent of decay, and intensity and duration of the devolatilizing pressure have formed different kinds of coal, now known separately as peat, cannel coal, and different forms of bituminous and anthracitic coals. These different types are usually classified with reference to the relation between the fixed carbon content and percentage of volatile matter in the coal.

The average proximate analysis, chemical composition, and lower heating value, in B.t.u. per pound, for various furnace coals are given in Table 1.

The preparation of bituminous coal has never been as efficient as that of anthracite, but the practice has recently improved greatly in respect to the washing and sizing of the coal, because it has been realized that clean, sized coal is more economical, not only in actual coal consumption but in the labor involved in storing and handling and in control of combustion. E. S. Moore, in his volume, *Coal*, states that in 1922 Illinois was the farthest advanced of the states in this respect, with only 20 per cent of its coal sold as "run-of-mine"; he gives the following classification of sizes, which, however, vary in different fields:[2]

Lump:	Over 6 in.
Egg:	Over $3\frac{1}{2}$ in. through 6 in.
No. 1 Nut:	Over $1\frac{3}{4}$ in. through $3\frac{1}{2}$ in.
No. 2 Nut:	Over 1 in. through $1\frac{3}{4}$ in.
No. 3 Nut:	Over $\frac{3}{4}$ in. through 1 in.
No. 4 Nut:	Over $\frac{1}{4}$ in. through $\frac{3}{4}$ in.
No. 5 Nut:	Through $\frac{1}{4}$ in.

[1] For full explanation of coal formation, see *Fuels and Their Combustion*, by Haslam and Russell.

[2] Reprinted by permission from *Coal*, by Elwood S. Moore, published by John Wiley & Sons, Inc.

TABLE 1

Comparison of Various Industrial Heating Coals *

	Moisture, Per Cent	Volatile Matter, Per Cent	Fixed Carbon, Per Cent	Ash, Per Cent	Sulphur, Per Cent
Lignite:					
Low-grade...	38.81	25.48	27.29	8.42	0.97
High-grade..	33.38	27.44	29.62	9.56	0.94
Sub-bitum.:					
Low-grade...	22.71	34.78	36.60	5.91	0.29
High-grade..	15.54	33.03	46.06	5.37	0.58
Bituminous:					
Low-grade...	11.44	33.93	43.92	10.71	4.94
High-grade..	3.42	34.36	58.83	3.39	0.58
Semi-bitum.:					
Low-grade...	2.70	14.50	75.50	7.30	0.99
High-grade..	3.26	14.57	78.20	3.97	0.54

	Hydrogen, Per Cent	Carbon, Per Cent	Nitrogen, Per Cent	Oxygen, Per Cent	B.t.u. per Pound
Lignite:					
Low-grade...	7.09	37.45	0.50	45.57	6,347
High-grade..	6.77	41.31	0.67	40.75	7,189
Sub-bitum.:					
Low-grade...	6.14	52.54	1.03	34.09	9,207
High-grade..	5.89	60.08	1.05	27.03	10,557
Bituminous:					
Low-grade...	5.39	60.06	1.02	17.88	10,958
High-grade..	5.25	77.98	1.29	11.51	14,134
Semi-ibtum.:					
Low-grade...	4.58	80.65	1.82	4.66	14,121
High-grade..	4.76	84.62	1.02	5.09	14,699

* *Smithsonian Physical Tables*, Vol. 71, No. 1, Table 263. Reprinted by permission.

When coal is hand-fired at the furnace, it is generally wheeled from a storage pile in the yard. The same is true of most stoker-fired furnaces, as the installation is seldom large enough to warrant the use of costly conveyors and large overhead storage bins.

The methods in use for the application of coal in solid form to industrial heating are hand firing, stoker firing, and the use of powdered coal. As stated in the first chapter, hand-fired coal was about the only fuel in use for industrial heating until about 1900, when it was largely replaced by oil, coal gas, and other more easily utilized fuels, returning to favor a very few years ago when stokers and powdered-coal firing were developed to permit the use of coal in a form having some of the advantages of other fuels. The use of coal in these two forms is finding increasing favor on account of the advantages of price and steady supply which coal possesses, and the use of this fuel will probably continue to grow, but the history of the hand-fired arrangement appears to be almost at an end except on old furnaces still in operation. It has few advantages, and is not to be recommended for most types of work.

The use of stokers seems to the author to have a broad field of application. Many very successful installations have been made (a forging furnace is shown in Fig. 8), and economical coal consumptions are obtained with industrial furnace stokers. The equipment required is comparatively cheap, with good control features, the upkeep cost is low, and the application is general to any furnace which is large enough to require the heat equivalent to the capacity of a small stoker and which is used for heating processes that are not too exacting, such as reheating, forging, and annealing of castings. In its present state of development stoker firing is not suitable for accurate heat treating requiring close control of temperature and atmosphere entirely free from air or foreign matter, and it will probably never be suitable for this class of work; but for the comparatively rough, continuous or semi-continuous processes, it appears to be ideal. Care must be exercised in the selection of the stoker, and not all coals can be satisfactorily handled in this

way. Stokers may be roughly divided into two classes: those that push the fuel over an immovable grate surface, and those in which the fuel remains motionless on a moving grate. The former will not satisfactorily handle a coal very high in ash because of the clinkering of this ash by constant agitation, while the latter type is entirely unsatisfactory for coking coals which require agitation in the early stages of combustion to prevent cementing action of the tarry substances of the fuel

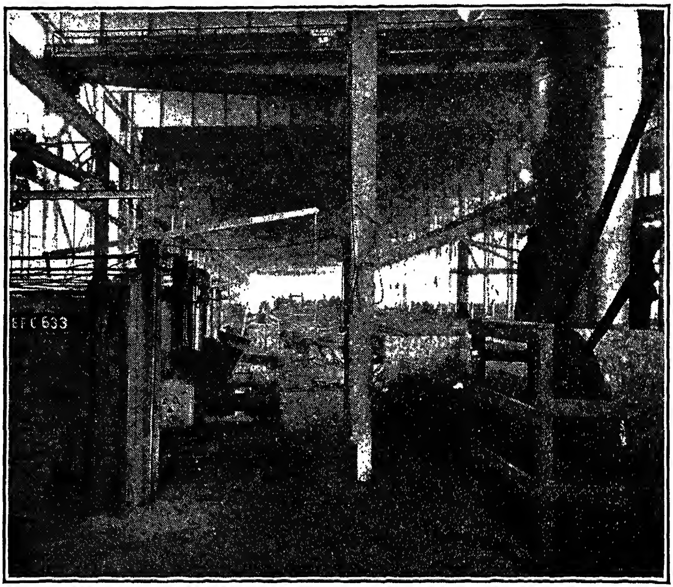


FIG. 8.—Stokers Applied to Forging Furnace.

bed. Underfeed stokers (Fig. 9 shows details of one type of underfeed stoker) have had the commonest application so far to industrial furnaces, and, since these belong to the first class of stokers, the use of stoker-fired coal on furnaces has been limited to those coals that are not too high in ash and do not contain much low-fusing ash. Most coals are satisfactory in this respect, and stokers will utilize poor grades of run-of-mine and screening sizes which it would be impossible to handle with a hand-fired arrangement. Air for combustion is supplied

mechanically from a blower at several ounces per square inch pressure, and usually enters the fuel bed through suitable tuyeres in the stoker grate.

At the present time the use of powdered coal is confined chiefly to cement kilns, boilers, and open-hearth furnaces, and has made rapid strides in these applications; but there are some successful applications to heating furnaces, including even such small furnaces as rod-heating and bolt-heating furnaces. There are two methods of preparation: the unit system, consisting of a separate machine delivering coal to each furnace or unit; and the storage system, in which the coal is prepared and stored in a

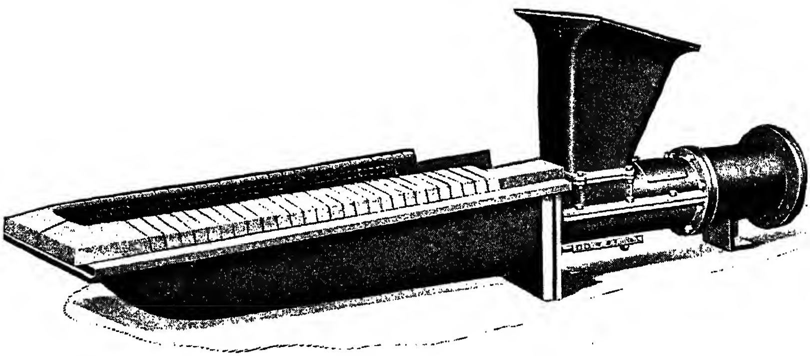


FIG. 9.—An Underfeed Stoker—Note Air Tuyeres.

large bin from which it is distributed to the various units as needed. The storage system is too expensive to be installed for a few furnaces, but in cases where the system is already installed for other purposes it can be readily adapted to a large number of furnace types. In either process of preparation, the coal is dried to about 1 per cent of moisture, crushed, and pulverized so that about 95 per cent will pass through a 100-mesh sieve. It is then mixed with a proper amount of air for combustion and fired into the furnace through a suitable burner. (Fig. 10 shows powdered-coal burners.) The advantages of powdered coal are that the form in which the coal is supplied permits of excellent combustion with complete mixing of fuel and air, and of easy control of furnace temperature and atmosphere.

Also, the powdered form is the only way in which many clinking coals can be satisfactorily utilized. These advantages frequently more than offset the cost of preparation, but coal in this form is quite hard on the furnace brickwork, which increases the cost of upkeep and must be taken into consideration. Because of ash particles which cannot be entirely eliminated, the use of powdered coal is excluded from any furnace for fine heat treating, but for other purposes it is worthy of careful consid-

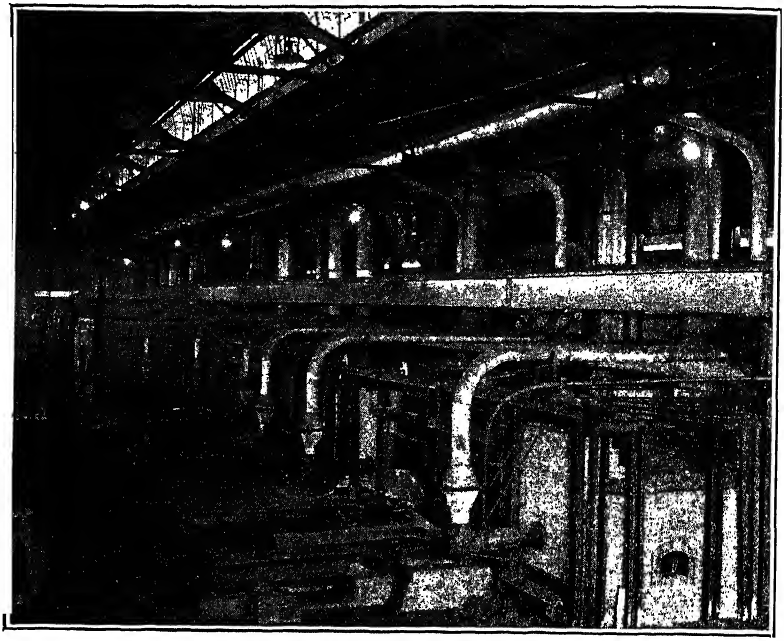


FIG. 10.—Powdered Coal Burners Applied to Furnaces.

eration, particularly in cases where it is already available for other heating purposes in a plant.

Coal is commonly called the basic fuel, because it is the most abundant and cheapest of all natural fuels and is the base for the manufacture of most artificial fuels. It is very much cheaper than other fuels for the same heat content, but its solid form offers difficulties in the way of taking advantage of this fact. Stokers and powdered coal have greatly increased the efficiency

and accuracy of control, but the dirt and awkwardness of handling continue to prevent its wide application in manufacturing plants.

Liquid Fuels.—The only liquid fuels in common industrial use are fuel oil and tar, although considerable research work is now being done on the problem of the liquefaction of coal. Tar is a by-product of the manufacture of coke and is chiefly used in open-hearth and rolling-mill furnaces which are close to the source of supply. Fuel oil is the residue of petroleum after the light gasoline and heavy lubricating stocks have been distilled off, and varies greatly with the geographical location of the district from which the petroleum originates. For industrial use, it varies in gravity from 10 to 34 deg. Baumé, with a variation in heating value from 18,000 to 19,500 B.t.u. per lb.

The heating value of fuel oil varies with the gravity on the Baumé scale. This variation is such that oils having a Baumé gravity of 10 deg. usually contain about 18,500 B.t.u. per lb., and other equivalents are as follows: 20 deg. Bé., 19,000; 30 deg. Bé., 19,400; and 40 deg. Bé., 19,900 B.t.u. per lb. These values are lower heating values. as previously explained.

The density also varies with the Baumé gravity, so that for 10 deg. Bé., the density is about 8.4 lb. per gal.; for 20 deg., 7.8 lb. per gal.; for 30 deg., 7.3 lb. per gal.; and for 40 deg., 6.9 lb. per gal. With these data it is possible to convert the calorific power to terms of B.t.u. per gal., as is frequently necessary in calculations. For example, the heating value per gallon for an average fuel oil of 28 deg. Bé. gravity and 18,500 B.t.u. per lb. will be 136,900 B.t.u. The heavy oils with low heat content per pound contain so many pounds per gallon that on the gallon basis they contain more heat than high-grade oil. Fuel oil is sold by the gallon, so that heavy oils are not only cheaper per gallon but contain more heat per gallon than light oils.

The coefficient of cubical expansion of fuel oil is about 0.0004 per deg. Fahr. (0.00038 average for oils below 30 deg. Bé. and 0.00043 for oils above 30 deg. Bé.). Information on flash points, cold tests, and other physical properties not needed for the purposes of this book can be readily obtained from many

texts on the subject of oils. The specific heat of fuel oil varies betwen 0.40 and 0.50 for temperatures up to 200 deg. Fahr. Volume equivalents which are frequently needed in fuel-oil calculations are as follows:

1 U. S. gal.	= 231 cu. in = 3.79 liters.
1 U. S. barrel	= 42 U. S. gal.
1 Imperial gal.	= 4.54 liters.
1 Imperial gal.	= 1.2 U. S. gal.
1 Imperial barrel	= 50 U. S. gal.

The atomization of fuel oil in burners is directly affected by the viscosity of the oil, which, in turn, is a function of its temperature. The ideal viscosity is about 300 Saybolt seconds (time required to pass 60 cc. of oil through a standard Saybolt viscosimeter), which corresponds to 8 Engler viscosity, referred to water. The amount of heating (which must not exceed the flash point of the oil) varies with the oil, and is shown for some representative oils in Fig. 11. As a general rule, oils of lower than 27 deg. Bé. gravity should be heated for best results, and the following are recommended temperatures extracted from Fig. 11:

Deg. Bé.	Deg. Fahr.
10	265
15	185
20	125
25	90

Table 2 is a summary, for all furnace fuels, of data that are of use in calculating combustion values. The chemical analysis given for fuel oil is representative for all fuel oils, as there is comparatively little variation. The values of combustion air required and the amount of flue gases produced are used in the calculation of fuel consumption, and the determination of these values is discussed further in Chapter V.

The specific gravity of coal tar at 60 deg. averages 1.14, so that the average density is:

$$\frac{1.14 \times 62.4 \text{ lb./cu. ft. (water)} \times 231 \text{ cu. in./gal.}}{1728 \text{ cu. in./cu. ft.}} = 9.49 \text{ lb./gal.}$$

The average heating value for coal tar is 15,800 B.t.u. per lb., so that the heat per gallon is:

$$15,800 \times 9.49 = 150,000 \text{ B.t.u.}$$

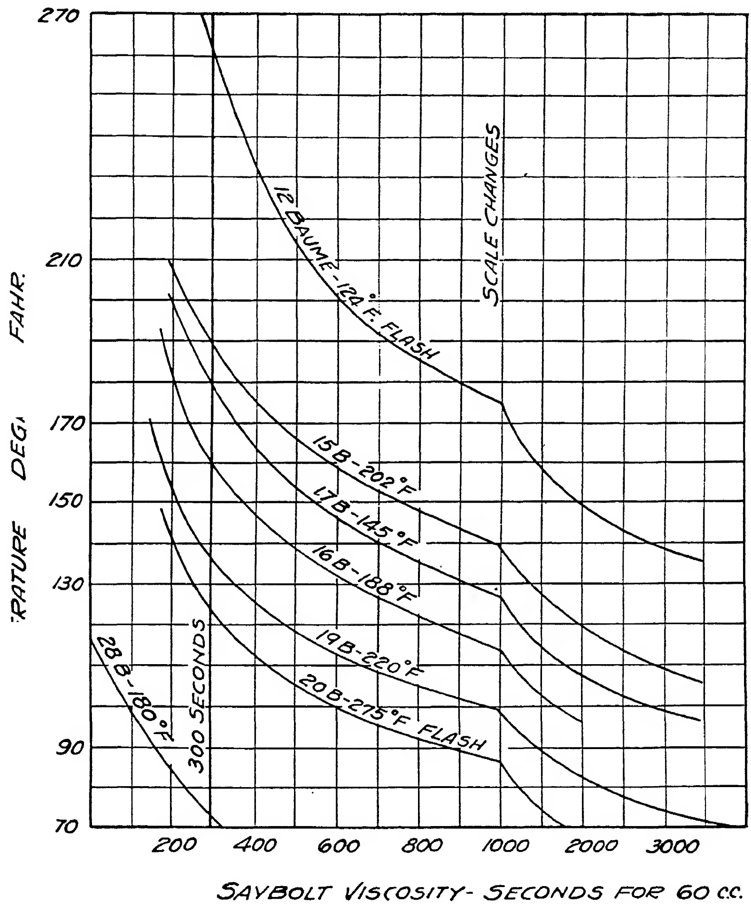


FIG. 11.—Viscosity of Fuel Oils at Various Temperatures.

The coefficient of cubical expansion is about 0.0008 per deg. Fahr. The viscosity in Saybolt seconds for tar at various temperatures is as follows:

Deg. Fahr.	Seconds
83	1450
93	950
100	590
110	380
120	260
140	135
180	70

The preparation and handling of fuel oil in a plant start with the storage tank. Oil is stored in a large storage tank, designed to conform to local fire regulations, located so that the oil can be pumped directly from the tank car, and provided with steam coils to keep the oil sufficiently warm to pump easily. From the storage tank it is pumped to the burners by means of a steam-driven or electric pump, complete with strainers, gauge, and relief valve, the overflow from the relief valve being returned directly to the tank in all cases so that air or gases trapped with the oil can be vented to insure a steady oil supply to the burners. An oil heater can be installed in this line to obtain the most efficient viscosity of the oil for atomization, as discussed in the preceding paragraph, and consequently to increase the efficiency of operation of the burners. Most of the oil burners for industrial furnaces are designed to operate on either high pressure, from 20 to 100 lb. per sq. in. or low pressure, from 8 to 24 oz. per sq. in. The high-pressure burners will operate on either air or steam, while the low-pressure type require air from a fan or turbo-blower. Burners for operation on 8 to 10 oz. pressure are the most popular of all types at present, because of the low first cost of blower equipment and low cost of compressing the required air. Figure 12 shows a typical low-pressure burner installation, including automatic cutoff valve for shutting off the oil in case the air supply fails. The various parts of an oil-burning system will be discussed in more detail in Chapter VII, dealing with auxiliary equipment.

Fuel oil is always fired into a furnace by means of some form of burner, which is the atomizing agent that divides the oil into very small particles for mixture with the combustion air. Part

TABLE 2

PROPERTIES OF FUELS

Fuel	Average Chemical Analysis, Per Cent by Weight for Solids and Liquids; Volume for Gases												Lower Heating Value, B.t.u. per Unit of Fuel *	Density, Pounds per Unit, Standard Conditions	Cold Combustion Air, Cubic Feet per Unit Perfect Combustion	Cold Flue Gases, Cubic Feet per Unit	Density of Flue Gases, Pounds per Cubic Foot
	S	H_2	C	N_2	O_2	CH_4	C_2H_6	CO	CO_2	Illuminants	Ash	C_2H_4					
Lignite	0.9	6.8	41.3	0.7	40.7						9.6		7,189	40	71	82	.0760
Sub-bituminous coal	0.6	5.9	60.1	1.0	27.0						5.4		10,557	To	103	112	.0782
Bituminous coal	0.6	5.2	78.0	1.3	11.5						3.4		14,134	50	137	143	.0790
Semi-bituminous coal	0.5	4.8	84.6	1.0	5.1						4.0		14,669	Lbs./C.f.	148	153	.0795
Cannel coal	1.0	6.8	73.3	1.3	8.3						9.3		14,251	Piled	139	146	.0782
Fuel oil—24° Bé.		13.0	83.7	2.0	1.3								140,000	7.55	1410	1505	.0760
Coal tar	0.8	6.0	86.7	0.1	3.0		$H_2O = 3.3$				0.1		150,000	9.49	1500	1560	.0785
Natural gas (Ohio)				5.0		80.3	14.7						970	.0491	10.11	11.19	.0730
Coke-oven gas		53.0		12.1		28.1		6.0	0.8				425	.0288	4.08	4.79	.0708
Blast-furnace gas				65.0	0.1			27.8	7.1				90	.0767	0.66	1.52	.0830
Raw producer gas		12.5		56.5		3.0		20.5	7.5				138	.0674	1.07	1.91	.0780
Clean producer gas		13.5		54.8		3.0		19.0	9.7				128	.0677	1.06	1.90	.0780
Coal gas		47.0		2.3		34.0		9.0	1.1			6.6	569	.0313	5.51	6.23	.0715
Blue water gas		52.9		4.7		2.2		36.8		3.4			287	.0342	2.35	2.87	.0740
Carburetted water gas		35.2		1.8		14.8		33.9	1.5			12.8	535	.0454	4.88	5.54	.0750
Oil gas		58.4		3.8		28.8		4.4	1.2	3.4			440	.0226	4.23	4.88	.0705

* Units are pounds for coals, gallon for oil and tar, and cubic feet for gases.

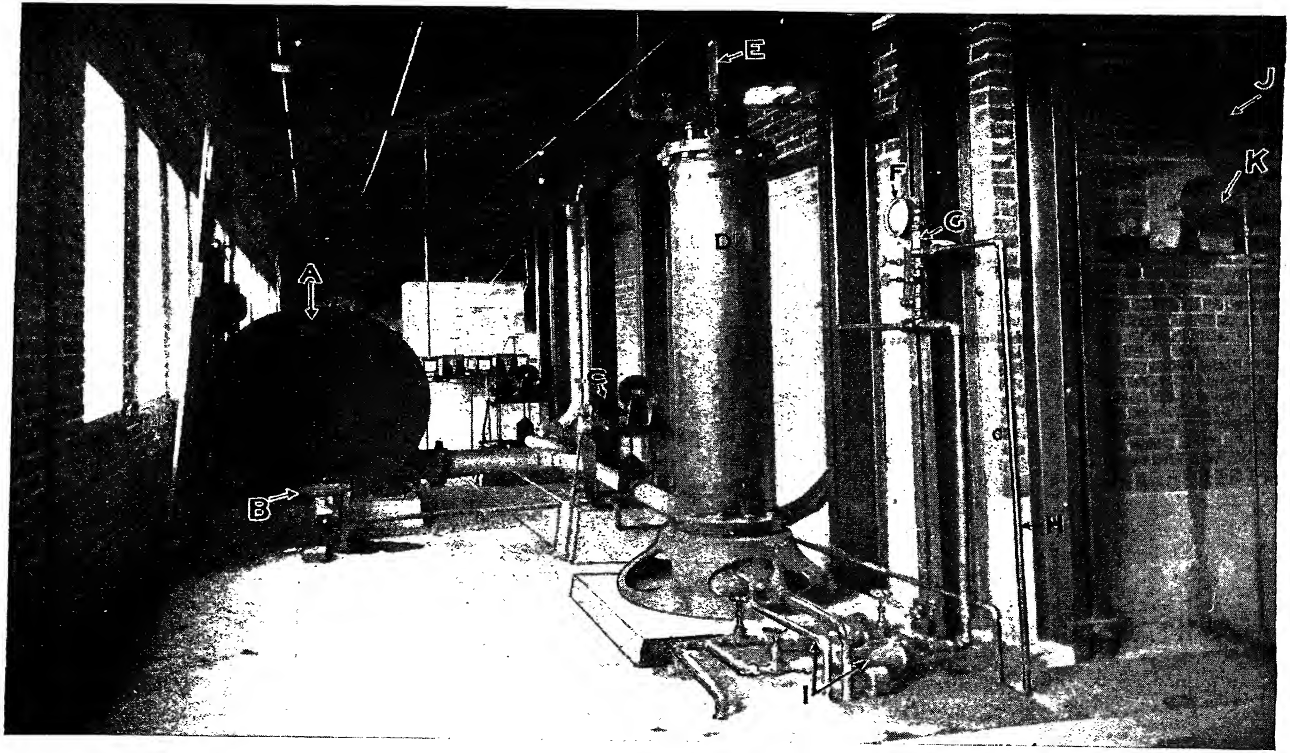


FIG. 12.—Typical Oil-burning System.

(A) Blower,
(B) Automatic cut-off valve,
(C) Automatic oil and air control.
(D) Oil heater,
(E) Oil thermometer,
(F) Oil pressure gauge.
(G) Relief valve,
(H) Return oil line to tank,
(I) Duplex strainers.
(J) Air blast gate,
(K) Oil burner.

or all of the air is supplied through the burner, and there are many different arrangements of the burner interiors for insuring violent mixture of the air and oil in order to reduce stratification. The fineness of the atomization and the initial mixture of the air and oil are functions of the burner, but efficiency in the actual burning of the mixture depends upon the arrangement of the furnace and is entirely out of the control of the burner. This fact is often overlooked. The burner and the furnace are dependent upon each other, but the furnace is, if anything, the more important, because the most efficient burner will not insure high efficiency in a poor furnace, while an average burner will give good results in conjunction with an inherently efficient furnace.

Fuel oil has a general application to almost any kind of industrial furnace, and few processes can be mentioned in which it has not been successfully applied. It can be much more easily regulated than coal, can be handled with lower labor costs, due to absence of ashes, is more easily stored and handled, and requires less expensive apparatus for its combustion and preparation; but availability of supply and increasing expense are becoming items of growing importance in comparisons between it and other fuels. It is much easier to control the amount of fuel burned when oil is used than with any form of coal, with the exception of powdered coal; and the ease of control of proper air to fuel ratios allows for many satisfactory devices for automatic control, all of which tend to make the efficiency of oil burning higher than that of coal burning. With improvements as they exist at present, it is generally accepted that the efficiency of utilization of the heating value of the fuel is 10 to 20 per cent higher for oil than for coal.

Gaseous Fuels.—Natural gas is the only natural gaseous industrial fuel in use, the remainder of the gaseous fuels being made from coal or oil, either as a direct product or as a by-product of some industrial process. Coal gas (also called illuminating gas, manufactured gas, or city gas) is made by the destructive distillation or carbonization of coal; blue water gas, by the reaction of steam with incandescent carbon; carburetted water

gas, by the addition of gaseous products of thermal decomposition of oils to blue water gas; oil gas, by the cracking of oils into gas; and producer gas, by the partial combustion of coal in the presence of air or steam. These are all direct products; the by-product gases are coke-oven gas, which is given off during the process of making coke from coal in by-product ovens, and blast-furnace gas.

The composition of most of these gases varies with the part of the country from which the coal or oil is obtained, as is also true of natural gas. Some idea of this variation for natural gas, and the variation in yield and calorific values for coal gas and producer gas may be had from the accompanying Tables 3 and 4, both taken from Poole's *Calorific Power of Fuels*, published by John Wiley & Sons, Inc.

TABLE 3

NATURAL GAS FROM VARIOUS LOCALITIES

	CH_4	C_2H_6	CO_2	N_2	B.t.u. per Cubic Foot at 60 Deg. Fahr.	Specific Gravity
Fort Worth, Tex.	51.1	10.0	......	38.9	691	0.76
Dallas, Tex.	50.6	10.9	0.1	38.4	702	0.77
Oklahoma	95.2	......	1.3	3.5	960	0.58
Louisiana	97.3	......	0.4	2.3	1009	0.59
Ohio	80.3	14.7	......	5.0	1068	0.65
Kentucky	77.8	20.4	......	1.8	1143	0.66
Alma, N. Y.	68.8	31.1	......	0.1	1241	0.71

Blast-furnace gas averages 85 to 100 B.t.u. per cu. ft. in heating value; coke-oven gas, about 500 B.t.u. per cu. ft.; blue water gas, 300 B.t.u. per cu. ft.; carburetted water gas, 400 to 600 B.t.u. per cu. ft.; and oil gas, 450 to 650 B.t.u. per cu. ft. The average values for percentage composition of some of these gases are given in Table 2, together with combustion data for all furnace gases.

The speed of ignition for industrial gases varies according to the composition. Gases with high hydrogen content ignite and burn more rapidly, and with a hotter flame, than those with a large proportion of inert gas. Coke-oven gas, coal gas, and water gas burn so readily as to be explosive in nature, while blast-furnace gas is very sluggish and sometimes almost impossible to burn without the use of preheated air of combustion to sustain ignition. Natural gas is between the two extremes, which helps to make it the ideal gaseous fuel.

TABLE 4

COAL GAS AND PRODUCER GAS FROM VARIOUS COALS

	Coal Gas		Raw Producer Gas	
	Cubic Foot of Gas per Pound Dry Coal	B.t.u. per Cubic Foot	Cubic Foot of Gas per Pound Dry Coal	B.t.u. per Cubic Foot
Pennsylvania	5.0	550	63.4	159.5
Kentucky	4.9	578	64.0	176.0
New Mexico	4.7	606		
California	5.2	566	32.1	158.3
West Virginia	5.3	555		
Wyoming	7.0	502	41.7	146.6
Colorado	5.0	550		
Tennessee	5.7	575		
Alabama	5.3	538	75.4	152.0
Illinois	4.3	568	45.5	168.0
Michigan	4.7	526		
Arkansas	....	....	61.9	130.0
Indiana	....	....	55.7	154.7
Kansas	....	....	66.0	128.9

Industrial gases are prepared and distributed by utility companies. The service performed by these companies includes the actual piping of the gas into the plant where it is used. This constitutes one of the greatest advantages of these gases.

The general characteristics of the burners used for industrial gases are the same for all gases, although different proportions are required because the compositions require different ratios of gas and air for combustion. For example, natural gas requires about 10 cu. ft. of air for each cubic foot of gas burned, while coal gas requires only about 5 cu. ft., but this is taken care of by changing the relative sizes of the air and gas openings. Almost all modern gas burners for heating furnaces are arranged for automatically maintaining the correct gas-to-air ratio for all rates of fuel consumption, but there are numerous methods of accomplishing this result and a variety of gas and air pressures are used. In some burners the air or the gas is supplied under pressure, varying from a few inches of water up to 25 lb. per sq. in., and all or part of the other constituent is introduced by inspirating action. In other burners, the air and gas are both supplied under pressure and mixed at the burner in automatically maintained proportions by interconnecting pressures of air and gas; or the gas and air can be mixed at the blower, and the mixture carried to the furnace. Some of the cruder gases, such as coke-oven gas and raw producer gas, which contain tar and other impurities, are not so readily handled in these refined types of burners, and are usually burned by mixing gas and air inside the furnace chamber with hand control of the gas and the air supply. Information on the comparative advantages of the different types and details of construction can be readily obtained from the gas-burner manufacturers, who, with the assistance of public utility companies, have worked out valuable data from the results of many tests. Figure 13 shows a typical modern gas-fired furnace with automatically controlled burners. Design data for gas burners are discussed further in Chapter VII.

The advantages outlined for fuel oil are even more pronounced in the case of gaseous fuels, the chief limitation to their use being the cost. Gas is extremely easy to handle and has high efficiency and ease of control, because its finely divided physical nature is ideal for intimate mixture of combustion air. The products of combustion are cleaner than those of other fuels, and this fact allows the use of most gases in processes

where very careful heat treating of finished surfaces is desired. Also, the combustion of gas requires a much smaller space, and combustion is more readily maintained than with other fuels, so that finer and better precision apparatus can be built for its use than is possible with the cruder fuels. These advantages, together with cleanliness, make gas stand out, with electricity, as a dominant form of heat energy for fine work. Gas is not

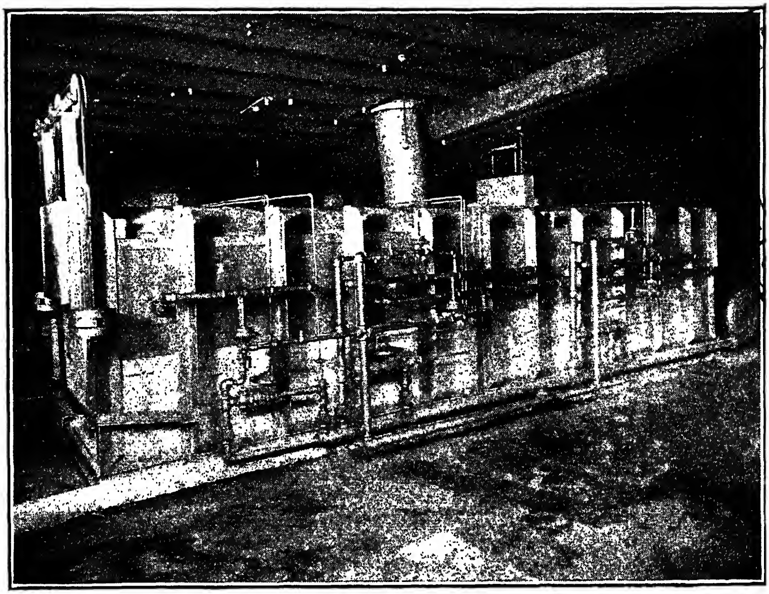


FIG. 13.—A Gas-fired Furnace—Low-pressure Burner System.

the universally correct fuel that it is sometimes claimed to be, but it undoubtedly has a broad field of application and a long and growing future ahead of it.

Electricity.—This book is intended to cover primarily the design of fuel-fired furnaces, but any discussion of fuels would be valueless without respectful reference to electricity. Heat in electric furnaces is obtained from the resistance of suitably arranged resistance units to the passage of a current of electricity. This current, supplied by public utility companies, as is gas, is usually 110, 220, or 440 volts, and may be direct current

or alternating current of any commercial phase or frequency. The measure of the energy utilized is the kilowatt-hour. One KW-hr. equals 3415 B.t.u. per hour, and this relation is used in comparing electricity with combustible fuels.

Electricity is the chief competitor of gas and oil for refined heat treating, and in many large concerns, such as automobile factories, it has largely replaced oil and gas as a furnace-heating medium for fine work, although gas continually threatens its superiority. The cleanliness of electricity is its chief appeal and, together with the fact that automobile companies are large enough to buy electric current in sufficient quantities to make the price low, has largely accounted for its wide application in these concerns. Unless the price of electricity becomes considerably lower than it is at present—and this does not appear probable—its application will be limited to comparatively fine heat-treating processes which require a clean finished surface after heating, such as the heat treating of machined parts or enameling, or which require extremely accurate temperature control. The upper temperature limit of metallic resistors is about 1850 deg. Fahr. (other materials have been developed for forging furnaces at higher temperatures but do not have extensive application), and it has been found quite as difficult to obtain a surface free from scale with electric heat as it is with oil or gas as fuel; but the surface will be free from atmospheric impurities, which is frequently of sufficient importance to warrant the additional expense of electricity. Its advantages will always keep electricity in a position of importance, but other fuels are keen and jealous competitors and have been surprisingly successful in keeping up with electricity by constant improvements, made imperative by the threat of electric heating.

Comparative Costs of Fuels

In discussing this question the following items must be taken into consideration: the geographical location of the plant in which the fuel is to be burned; the present and probable future supply of the fuels considered; comparative costs of the fuels

delivered to the furnace on the basis of heat content; and overall costs, including savings in material heated and other items.

Geographical Location and Supply.—The determination of costs of fuels is an extremely difficult matter on which to prepare any general data, because of the many factors which affect these costs and the wide range of prices which ordinarily prevails. The following data are given merely as a general indication of relative prices of various fuels as a guide in their consideration for heating furnaces, and to give some idea of the importance of the geographical location of the plant in the selection. With such a general idea in mind, it should be easier to sift the statements of local representatives of the fuels under consideration and make allowance for the exaggeration which sometimes exist in their statements. It should be remembered, however, that each case is a separate problem, and careful study of local conditions is essential to the determination of the best fuel policy.

Coal.—Although the costs of coal are subject to violent fluctuations which make it risky to give general figures, Table 5 gives some idea of the delivered prices of high-grade coal existing in different parts of the country for the years 1912 and 1926, the latter figures possibly being slightly high because of unusual conditions.

TABLE 5

DELIVERED COSTS OF HIGH-GRADE COAL, DOLLARS

	1912	1926
Boston	4.75	6.25
New York	3.90	4.85
Philadelphia	3.90	4.85
Baltimore	3.80	4.75
Pittsburgh	3.75	4.75
Columbus	3.10	3.85
Cleveland	3.20	4.30
Chicago	2.65	4.50
Birmingham	2.80	3.50
Kansas City	5.30	6.50

Although the figures in this table cannot be considered as an entirely accurate picture of coal prices, they indicate that the price of coal is increasing very slowly, which is logical in view of the fact that there is plenty of coal yet available and a large supply in the future keeps the price fairly steady, at least as far as average prices are concerned. This condition will probably exist until such time as the resources approach exhaustion, which will not occur for several generations at least.

Fuel Oil.—There is such a vast difference of opinion in regard to the future of oil as an industrial fuel that it is difficult to set down any reliable consensus of opinion as to where its price will be found in the future. There are many authorities who state that the available oil supply is limited to from eight years to two generations, and that the price of oil will be exorbitant for industrial work because it will be used for making gasoline and for other purposes for which it will be needed more than in the industrial field. Examination of available estimates of petroleum still in the ground, production figures, and data covering the enormous increase in the use of fuel oil in cracking processes to make gasoline and other products, makes this opinion appear to have considerable weight; but the disappearance of oil as a fuel will be retarded somewhat by the utilization of oil shale. Although the oil-shale industry is of no importance at present, it will eventually be very important as the increased demand and higher prices make it profitable to produce oil from low-grade material. The rate of disappearance of oil will be different for different parts of the country, depending upon the source of supply and other fuels available. In California, for instance, which is near the big source of supply and where other fuels are not available in large quantities, oil will be used long after it has become rare in coal regions like Pennsylvania, where the increasing efficiency of other fuels will tend to make the use of expensive oil uneconomical. It seems probable that the price of fuel oil will continue to advance in the future, and that it will remain an important furnace fuel only so long as the price is low enough to compete with other more stable fuels; but the decline in its use will be gradual because its advantages over coal in

many cases and its present cheapness compared with manufactured gases, together with the low first cost of equipment required, will make it a paying investment for some time. In Table 6 are shown the prices which have prevailed in the various oil fields and which are a good indication of the price trend. The figures for 1920 were high on account of the War and are interesting because they show the great instability of this fuel.

TABLE 6

AVERAGE PRICE OF FUEL OIL PER BARREL OF 42 GAL., DOLLARS *

	1900	1905	1910	1915	1920	1926
Appalachian Fields....	1.35	1.39	1.33	1.55	5.41	2.52
Lima Indiana.........	0.98	0.87	0.79	0.96	3.60	1.45
Illinois...............	5.00	0.64	0.59	0.98	3.71	1.45
Mid-Continental......	1.03	0.55	0.39	0.59	3.36	1.45
Gulf................	....	0.24	0.76	0.48	2.39	1.80
Rocky Mountain......	1.12	1.01	0.95	0.54	2.74	1.55
California............	0.94	0.25	0.49	0.42	1.85	1.20
Other States.........	0.74	1.07	1.33	1.70		

* From *Handbook of the Petroleum Industry*, by David T. Day, published by John Wiley & Sons, Inc.

Natural Gas.—The fate of pure natural gas for industrial fuel has been the same as that prophesied by some for fuel oil. There are statements to be found, dated as late as 1900, to the effect that the natural-gas resources had hardly been touched; but the increase in use was so unexpectedly great that to-day natural gas has practically disappeared from industry in some localities, because what gas there is left is so ideal for domestic use that it can command a price that puts it out of competition in industry.

Coke-oven Gas.—As stated previously, the use of this gas is at present confined to steel-mill furnaces or boilers, this practice being the most logical because it is cheap and economical to use the gas close to the source of supply. However, a large number of water-gas plants are being installed in connection with by-product coke ovens, because water gas mixed with coke-oven

gas has the high volatile constituents of carburetted water gas and is cheaper to make. It is quite probable that in a short time most of the coke-oven gas will be utilized in this way, and this gas is becoming more important in view of the increasing use of by-product ovens for the manufacture of coke. In 1910, only about 17 per cent of all manufactured coke, with the exception of gas-house coke, was made in by-product ovens, while in 1920 this percentage had increased to about 55, and by this time is probably in excess of 75 per cent of the total.

Producer Gas.—The use of this gas is becoming somewhat more general for large mill furnaces designed for heavy work, owing to improvements in the small gas producers. These small producers are sold at a comparatively low cost, and they make an inexpensive gas, well suited for the conditions required in reheating furnaces for rolling mills and similar furnaces. Egg and nut sizes of coal are desirable, but screenings can be satisfactorily utilized, the only necessity being low sulphur and fairly low ash content. The raw gas obtained is not clean enough for accurate work unless it is scrubbed, but it makes a hazy flame which is desirable for reheating operations. Clean producer gas can be stored in a gas holder to be distributed to furnace units as needed, while the raw gas must be kept moving on account of tar and dirt.

Blast-furnace Gas.—This gas is of too low a calorific power to be of much commercial value, and will probably continue to be used only for blast-furnace stoves and other processes within the mills.

Commercial Manufactured Gases.—These consist largely of coal gas and water gas, with oil gas in the western part of the country, and their use is one of the most rapidly increasing factors in industrial heating. The manufacture of these gases is just reaching the point where they can be utilized industrially to any extent; but the growth of the gas business in the few years since it has become really active indicates that in a very few more years these gases will be available in large quantities and at lower prices than now prevail. Some figures showing the production and prices of manufactured gases in various cities

are given in Table 7, made up from data in Brown's *Directory of American Gas Companies*, Editions of 1924 and 1927.

TABLE 7

VARIATION OF COST AND PRODUCTION OF MANUFACTURED GAS WITH GEOGRAPHICAL LOCATION

Location	Kind of Gas Supplied	Yearly Production, Millions of Cubic Feet		Average Calorific Value, B.t.u. per Cubic Foot		Minimum Price,* Dollars per Thousand Cubic Foot	
		1924	1927	1924	1927	1924	1927
Massachusetts:							
Worcester......	Coal gas......	123	......	540	533	1.35	1.35
	Water gas.....	963	1,277				
Salem..........	Coal gas......	158	170	540	530	1.30	1.30
	Water gas.....	164	169				
Springfield......	Coal gas......	758	864	536	533	1.35	1.35
	Water gas.....	890	1,057				
Connecticut:							
Hartford.......	Coal gas......	163	......	542	538	0.80	0.80
	Water gas.....	1,298	1,870				
New York:							
Brooklyn.......	Water gas.....	21,985	25,538	.....	552	1.10	1.10
Delaware:							
Wilmington.....	Water gas.....	997	1,041	.....	.....	1.20	1.20
Pennsylvania:							
Reading........	Water gas.....	862	1,119	522	525	0.90	0.90
Maryland:							
Baltimore......	Water gas; Coke-oven gas.	10,310	11,772	500	500	0.60	0.60
Georgia:							
Atlanta........	Coal gas......	513	552	580	576	1.15	1.15
	Water gas.....	992	1,049				
Ohio:							
Cleveland......	Water gas; Coke-oven gas.	459	259	549	600	1.00	1.00
Michigan:							
Detroit.........	Coal gas; Water gas; Coke-oven gas.	14,500	20,406	.....	.....	0.49	0.70
Illinois:							
Chicago........	Water gas.....	16,170	13,797	538	540	0.85	0.85
California:							
Los Angeles.....	Oil gas.......	76	108	850	850	0.53	0.53
	Reformed gas..	2,415	3,297				

* Based on a consumption of 200,000 cu. ft. of gas per month. The price is lower than given in some localities for greater monthly consumption.

Comparative Costs of Fuels.—This is an extremely difficult question to cover in a general way, and each case is a new problem; but the general method of procedure will be given, together with a very approximate general idea of the cost of preparation of fuel oil as an example. The determination of comparative fuel preparation costs is not at all difficult when all the conditions of a specific case are known, and the solution consists of the determination for each fuel of the total of the following charges:

1. *Charges on investment in equipment.*

   This item is often taken as a yearly charge of 22 per cent of the initial cost, made up of 6 per cent interest on the investment, 10 per cent depreciation, 3 per cent taxes and insurance, and 3 per cent maintenance and repairs. For comparison of costs of fuels delivered to the furnace, this percentage is of the auxiliary equipment necessary to handle, prepare, and fire the fuel. For overall cost comparison, the furnace must be included, as the cost of the furnace sometimes varies for different fuels, especially in the case of electric furnaces where the resistors are integral parts of the furnace and are costly.

2. *Expense of supplying combustion air.*

   The cost of air is an extremely variable item, depending upon the fuel, the percentage of total air mechanically supplied, the air pressure, and the efficiency of the compressor, blower, or fan used. The method of determining this item is to calculate the fuel and air requirements of the furnace, as explained in Chapter V, to determine the percentage of air to be supplied mechanically and the proper pressure for the combustion equipment under consideration, and to determine the power requirements of the compressor, blower, or fan of the correct size for supplying the desired air.

3. *Additional power requirements.*

   These include such items as power for operation of pumps, steam for steam heating of oil in oil-burning instal-

lations, and steam or power for operation of mechanically driven coal stokers, powdered coal crushers and pulverizers, and the like. The information for these items may be obtained from equipment manufacturers.

4. *Interest on stored fuel.*

This item is usually a charge of 6 per cent of the value of the average amount of fuel in storage at any time.

5. *Labor charges.*

These must be estimated from the number of men that will be required to operate the equipment necessary for each fuel, and the wages which must be paid to men having the necessary training to do the work.

The items to be included in a study of the costs of fuels vary greatly with the fuel. For hand-fired coal, the equipment required includes handling equipment in the yard only, and the air is usually obtained from natural draft at no expense, but the labor factor is large. For stoker-fired coal, the equipment investment is larger, and power is required for the stoker and air blowers (required stoker drive horsepower is from about 1.2 HP. for 250 lb. of coal per hour to 4.5 HP. for 2300 lb. per hour, and blower horsepower is from about 1.8 HP. to 6.0 HP. for the same capacities), but labor is reduced. With powdered coal, a very large investment is required for crushing and pulverizing, but the labor is still further reduced. Fuel oil requires tanks, blowers, and considerable piping, but no labor, because the furnace heater can readily take care of the operation. Gases require no equipment except burners and a small blower, very little power, and no labor (except for producer gas made in connection with the furnace, when producer equipment must be figured).

The following example illustrates in detail the method of cost determination for the case of fuel oil for one set of conditions:

Assume that the average oil consumption required will be 100 gal. per hour, and that the maximum capacity of the equipment must be 200 gal. per hour. The equipment is to be actually operated 52 weeks times $5\frac{1}{2}$ days per week times 8 hours per day, or 2288 hours, minus time lost

for holidays, repairs, shutdowns, etc., that is about 1600 hours per year, actual working time. The oil is to be atomized by air at 8 oz. per sq. in. pressure. Power to pumps and blowers costs 2 cents per KW-hr. Assume that oil costs $5\frac{1}{2}$ cents per gal., delivered to the railroad siding of the plant.

Then a maximum estimate of equipment required in this case will be found to be about as follows: burners, $500; blower, $1000; delivery pump, $500; unloading pump, $150; fittings, $100; storage tank, $1200; installation cost, $200. The total of these items is $3650, and 22 per cent of this figure is $800 per year, to be charged on the investment as previously explained. The cost per gallon of oil will be:

$$\frac{800 \times 100 \text{ cents}}{1600 \text{ hours} \times 100 \text{ gal./hour}} = 0.50 \text{ cent/gal.}$$

Oil requires about 1500 cu. ft. of free air (air at standard conditions of pressure and temperature) per gallon for perfect combustion, and the percentage of air mechanically supplied through the burner varies with the pressure. When air at 8 oz. pressure is used, about 60 per cent is supplied through the burner and the remaining 40 per cent induced by the burner from the atmosphere. (Burners using air at $1\frac{1}{2}$ lb. require about 30 per cent mechanical air, and those operating on air at 45 lb. only about 10 per cent.) Twenty per cent excess air in a furnace is a safe allowance with fuel oil, and about 25 per cent additional should be allowed in determining blower capacities for emergencies, so that in this case, the capacity of the blower should be:

$$\frac{\left\{\begin{array}{c}1500 \text{ cu. ft. air/gal.} \times 200 \text{ max. gal./hour} \\ \times 60 \text{ per cent} \times 1.20 \times 1.25\end{array}\right\}}{60 \text{ min./hour}} = 4500 \text{ cfm.}$$

free air at 10 oz. (to insure 8 oz. at the burners).

From Fig. 14, showing the average KW-hr. input required with motor-driven blowers for different pressures and capacities, for an average capacity of 100 gal. per hour and 8 oz. pressure at the burners, 0.07 KW-hr. per gal. is required. This times 2 cents per KW-hr. equals 0.14 cent per gal., the charge for air.

The usual pumping system is provided with a relief valve and return line to the tank to insure constant pressure at the

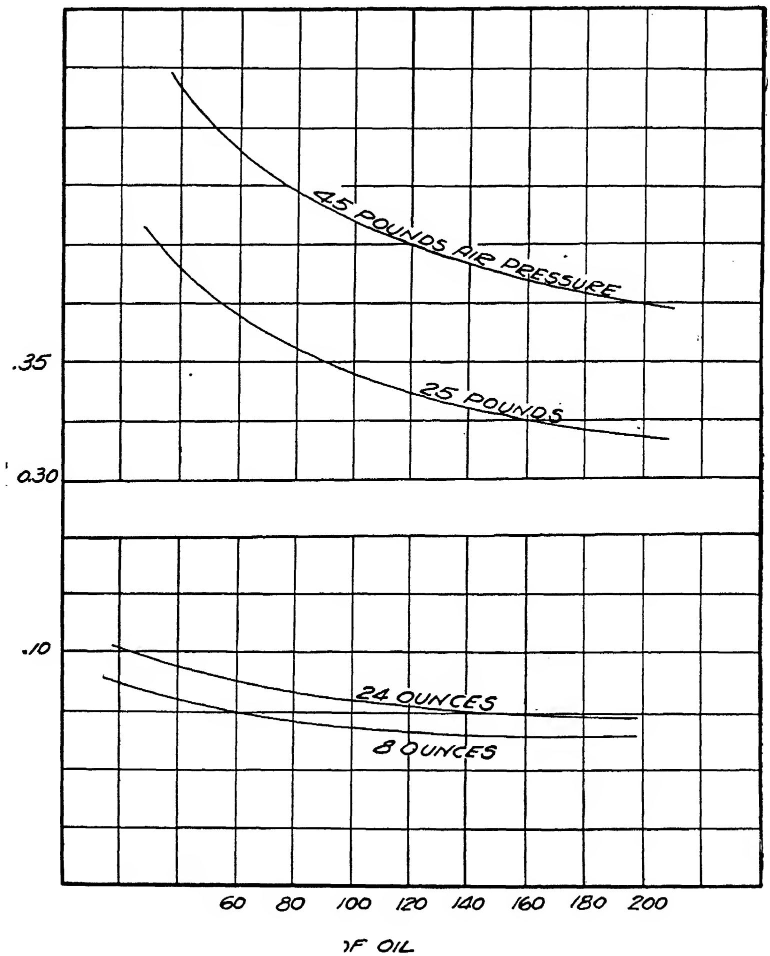


FIG. 14.—Power Input to Motor-driven Blowers, Supplying Air to Average Industrial Oil Burners.

burners, and about three times as much oil is pumped around this system as is required at the burners, so that in this case the pump must have a capacity of 600 gal. per hour maximum. The theoretical horsepower required for pumping is:

$$\frac{\text{Pressure, lb./sq. in.} \times \text{gal./min.}}{950} = \frac{40 \text{ lb./sq. in. average} \times 300 \text{ gal./hour}}{950 \times 60} = 0.2$$

Steam pumps for fuel-oil systems use about 200 lb. of steam per HP. Assuming that steam costs 0.06 cent per lb., the charge for pumping will be:

$$\frac{0.21 \text{ HP.} \times 200 \text{ lb./HP.} \times 0.06 \text{ cent/HP.}}{100 \text{ gal./hour}} = 0.02 \text{ cent/gal.}$$

If the pump were motor-driven, the pumping cost would be:

$$\frac{0.21 \text{ HP.} \times 0.746 \text{ KW/HP.} \times 2 \text{ cents/KW-hr.}}{100 \text{ gal./hour} \times 50 \text{ per cent overall efficiency}} = \text{about } 0.006 \text{ cent/gal.}$$

A storage tank should have a capacity of at least ten days' supply at the maximum rate, or:

$$10 \times 8 \text{ hours} \times 200 \text{ gal./hour} = 16{,}000 \text{ gal., say, } 20{,}000 \text{ gal.}$$

Average storage of fuel will be:

$$\tfrac{1}{2} \times 20{,}000 \text{ gal.} = 10{,}000 \text{ gal.}$$

Interest on the stored oil will amount to:

$$\frac{10{,}000 \text{ gal.} \times 5\tfrac{1}{2} \text{ cents/gal.} \times 6 \text{ per cent interest}}{1600 \text{ hours/year} \times 100 \text{ gal./hour}} = 0.021 \text{ cent/gal.}$$

Leakage may be as much as 2 per cent of the oil used, and the charge will be 2 per cent of $5\frac{1}{2}$ cents (the cost of the oil), or 0.11 cent per gal.

If the oil is to be heated, a charge must be added to cover the heating. Assume an oil temperature rise 100 deg. in a heater utilizing steam as the heating medium. Then:

100 gal./hour $\times$ about 7 lb./gal. $\times$ 0.50 specific heat $\times$ 100 deg. rise = 35,000 B.t.u. needed/hour.

If the steam is at 20 lb. per sq. in. pressure its heat content per pound is 1167 B.t.u. and the heat content of the hot water return is about 180 B.t.u. per lb., so that the heat utilized is

987 B.t.u. per lb. Neglecting radiation losses from the heater, the amount of steam needed is 35,000 B.t.u. divided by 987, or $35\frac{1}{4}$ lb. per hour. If the cost of steam is 0.06 cent per lb. the, charge will be $\frac{35\frac{1}{2} \times .06,}{100}$ or about 0.02 cent per gal. of oil.

The total charge for preparing oil in this case is, then, 0.50 plus 0.14, plus 0.02, plus 0.02, plus 0.11, plus 0.02, or a total of 0.81 cent per gal., and with $5\frac{1}{2}$ cents per gal. delivered cost, the cost of oil at the burners will be 6.31 cents per gal.

The cost of fuel to the furnace will vary greatly according to the amount of fuel handled, the amount of time the equipment is operated in a year, the relation of average to maximum capacity required, general efficiency of the equipment, etc. The cost of preparing oil is frequently greater than in the example given, but a charge of $1\frac{1}{2}$ cents per gal. will cover all cases where conditions are average, and a charge of 2 cents is ample for the worst conditions. Each set of conditions should be figured separately for accurate results, as no general rule will cover all conditions or all fuels. The comparative costs at the burner should always be determined in the selection of fuels. Without such figures it is impossible to judge the comparative advantages of the fuels considered.

No general rules can be made for the determination of the money value of the advantages of any fuel, which is essential in the determination of the overall costs of fuels. A partial list of these advantages includes the quality of the heated product obtained, reduction of oxidation, reduction in rejections of product from improper heating, amount of space necessary for equipment, quantity of production possible, cleanliness, and morale of workmen. All of the advantages and disadvantages for each fuel must be reduced to dollars and cents as closely as possible for each set of requirements and conditions. This can be done only by one thoroughly familiar with all of the pertinent factors that must be considered in order to obtain an overall value for each fuel.

There are one or two other considerations of importance, in addition to the nature and costs of fuels. One of these is the

question of space available. Coal requires a considerable space for storing and handling, oil comparatively little, and manufactured gases none at all. This is especially important in crowded plants, where space has a high value per square foot. Another consideration is that of equipment already available, and a survey should always be made of fuel being used in other parts of the plant. For example, if oil is used in other furnaces or processes there is frequently additional capacity available, and the cost at the burners can be figured very low because additional equipment does not have to be purchased. Also, in the case of gas or electricity, the usual sliding-scale rates can sometimes be taken advantage of, with the result that fuel or power costs all through the plant are cut by the use of this fuel on additional furnaces.

Conclusions

Having considered the more important items in some detail, let us now review them, and see again just what must be done in order to arrive at a decision on the fuel to be used. The steps are as follows:

First.—Keeping in mind the requirements of the particular process considered, study the most recent developments in the methods of application of the various fuels available. Eliminate all those fuels which would be entirely unsatisfactory from the nature of their combustion, dirt, lack of space required for installation of necessary equipment, or any other reason.

Second.—Calculate the probable average and maximum fuel consumptions necessary to do the work required. This procedure is explained in Chapter V.

Third.—Obtain the delivered cost of the remaining available fuels in the quantity required and for the district in which the plant is located. Collect as authoritative information as possible regarding the probable future price of these fuels in that district, for a period at least as long as the probable life of the proposed furnace.

Fourth.—Obtain information from the manufacturers of equipment for handling the possible fuels in the quantity re-

quired. This information should include complete costs of all apparatus required, air and power requirements, and estimates of labor to operate.

Fifth.—Estimate the cost at the furnace burner for each of the fuels, and with this figure and the amount of fuel required, calculate the cost of fuel per unit of product heated in the furnace.

Sixth.—Study the advantages and disadvantages of each fuel carefully, and convert them to money values of savings and losses per unit of product heated. The algebraic sum of these values, added to the cost of fuel obtained in the preceding paragraph, will give the overall cost of the fuel. This must include the comparative costs of the furnaces required with different fuels.

Seventh.—A careful study of these comparative overall costs and of the general items which cannot be readily converted to dollars and cents will usually point the way quite clearly to the proper fuel to use.

Although the task as outlined in this chapter requires patience and care, it is entirely possible to obtain reliable results if it is carried through, and the effort will usually be well repaid, because the cost of fuel in most plants is so large that a small percentage of saving will amount to a very considerable item.

CHAPTER III

APPLICATION OF HEAT AND FURNACE CAPACITY

In the preceding chapter we have seen the various phases to be considered in the first question—selection of fuel—incident to the installation of an industrial furnace. It was shown that with a general knowledge of the subject of fuels, some idea of the definite data required, and a method of arranging these data in such a way that they will lead to useful conclusions, the most logical fuel can be quite accurately determined. This is the first step, and is important because of the increasing importance of the fuel item in the costs of manufacturing. The assertion that it is frequently entirely neglected is proved by the large number of processes that are being carried on satisfactorily but at an excessive expense, because all of the fuels were not considered when the selection was made.

After the selection of fuel, the next important question that arises is the proper application of the heat in the fuel to the furnace and to the heating material. This question is important because the improper application of the heat in the fuel is one of the most frequent causes of dissatisfaction in the problem of furnace design. The reason for this is that, although the average executive or plant engineer has many sources of information on various fuels, and can become very enthusiastic when the subject of labor saving is mentioned, he has practically no information and little or no interest in the question of the interior arrangement of a furnace. It is a specialized question which he leaves to the bricklayer or entrusts to the furnace builder, a procedure which would be wise if it were not for the fact that the bricklayer in most cases, and the furnace builder too frequently, still relies on rule-o'-thumb methods. Probably no engineering

problem has offered more stubborn resistance to accurate theory and mathematical treatment than has the problem of heat transmission from flames and gases to heating material, and the causes are the large number of variables in practice and the lack of experimental data. The theory is gradually being developed, however, and the author believes that it will eventually eliminate guesswork and disprove many of the practical ideas now so frequently found.

The purpose of this chapter is to discuss in detail the various methods of furnace arrangement for heat development, considering the theory of each arrangement and the application of the various designs to definite furnace types. At this point, the difficulty in covering the question of furnace design piecemeal becomes evident, because the question of material handling, which will be discussed in the next chapter, is definitely interconnected with the classification of furnaces according to interior arrangement for proper heat application. In this chapter, therefore, the various kinds of furnaces will be considered with little attention to the effect of continuous and non-continuous designs, movable hearths, and similar features, which will be the subject of the next chapter. The question of furnace capacity and size will also be considered in this chapter, as it too is involved in the selection of suitable furnace types.

Furnaces may be classified, by interior arrangement for heat transmission, as underfired, overfired, sidefired, direct-fired, and muffle types. We shall first consider these in order named, before studying their applications. In addition to a consideration of operation, forms of fuel, and relative advantages in each case, some attention will be paid to the determination of important dimensions.

Underfired Type.—Underfired furnaces are so designated because the heat of combustion of the fuel is developed in a chamber located beneath the heating chamber of the furnace, the hot gases of combustion passing through suitable ports from the combustion chamber to the heating chamber, from which they are vented through suitable flues. Several variations of this arrangement are shown in Fig. 15. Sketches *a* and *b* show

the tile floor arrangement used in the small portable furnaces. In the first case, the tile is made with a lip at the side to prevent material from rolling into the combustion chamber, and is found in the small furnaces used for hardening tools and having a maximum hearth width of about 24 in. The second arrangement, with sidetile, usually of carborundum, is used on larger portable furnaces for heat treating and annealing which are built in widths up to about 48 in. In both cases the hearth is supported by side piers and center piers of carborundum brick. Sketch *c* shows the best method of construction for larger furnaces, with a brick hearth built into the furnace and supported by brick arch construction. The designs of Fig. 15 are for liquid or gaseous fuels, while Fig. 16 shows an underfired arrangement for burning

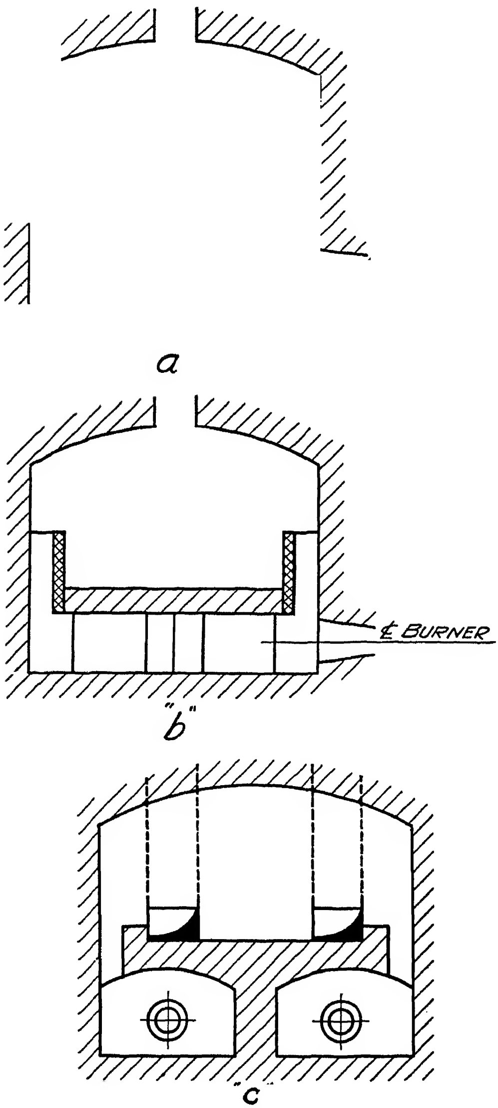


Fig. 15.—Underfired Furnace Arrangements.

handfired or stoker-fired coal to heat a double-chamber box annealing furnace such as is commonly found in sheet mills.

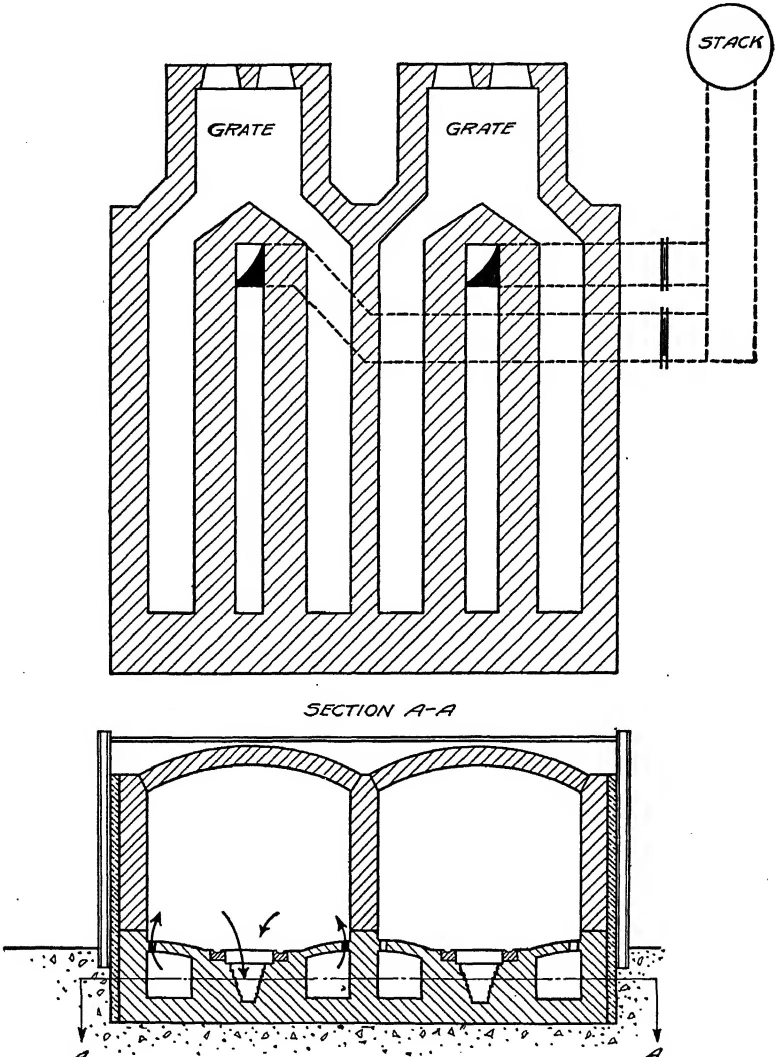


FIG. 16.—Underfired Furnace Burning Coal.

The purpose of the underfired construction is either to pro- the heating material from direct action of the flame and pre-

vent excessive scaling action by insuring complete combustion of the fuel before it strikes the stock in the case of high temperature furnaces (those over 1400 deg. Fahr.), or to obtain low temperature with fuels that require a high temperature to maintain combustion. Most fuels require a temperature above 1400 deg. to burn properly; therefore the fuel is burned in a small combustion chamber, which requires only a small quantity of fuel to maintain it at high temperatures, and the hot gases are taken into the heating chamber in just sufficient quantity to maintain it at the low temperature required. There is a common idea that the result is accomplished by the throttling action of the ports lowering the temperature of the gases as they pass into the heating chamber, but this is incorrect, as the same result can be obtained with considerable variation in port dimensions if the combustion chamber is small enough to be properly heated by the small quantity of hot gases required in the upper chamber. The fuel consumption of an underfired furnace is sometimes higher than that of the equivalent sidefired or direct-fired furnace, but only because the heating capacity of the underfired design is less per square foot of hearth area. The increase in radiation from the hot combustion chamber and the increase in fuel consumption when the flues are located in the roof, to prevent short-circuiting of gases from the lower chamber, are offset by the more complete combustion obtained.

As stated before, the size of the combustion chamber and—although this of lesser importance—the size of the connecting ports must be correctly determined, and both of these are fixed by the amount of fuel to be burned in the furnace. The method of determination of the fuel consumption will be studied in a future chapter, and, with this information, the determination of the proper dimensions is comparatively simple. The free volume of the combustion chamber, after the volume of all supporting piers has been subtracted, should be such that the average fuel to be required is liberated at the rate of about 12 B.t.u. per cu. ft. per sec., and the total area of all connecting ports should be such as to produce an average velocity of about $3\frac{1}{2}$ ft. per sec. of the hot gases. As an example, suppose

furnace of 3 ft. by 6 ft. hearth dimensions, operated at 1600 deg. Fahr., requires an average of $5\frac{1}{2}$ gal. of oil per hour to heat 550 lb. of steel per hour. This quantity of fuel oil will liberate about $10\frac{1}{2}$ cu. ft. of gases per second at 1900 deg. combustion chamber temperature (see Chapter V). The combustion chamber volume required will be:

$$\frac{5\frac{1}{2}\text{ gal. oil/hour} \times 137{,}000\text{ B.t.u./gal.}}{3600\text{ sec./hour} \times 12\text{ B.t.u. per cu. ft./sec.}} = 17.5\text{ cu. ft.}$$

and the total port area:

$$\frac{10.5}{3.5} = 3.0\text{ sq. ft.}$$

This corresponds to a combustion chamber 6 ft. long by 3 ft. 8 in. wide and 12 in. high, and ports on each side about 3 in. wide. Combustion chamber dimensions determined in this way will be found to work very well for furnaces having a temperature higher than about 1100 deg. Fahr. in the heating chamber. For lower temperatures the dimensions may be made smaller, or else bricks may be adjusted around the burner as shown for the low-temperature pot furnace in Fig. 24, to maintain the ignition temperature of the fuel.

The advantages of the underfired arrangement are that it allows very complete combustion and excellent control of temperature and furnace atmosphere. The disadvantages are as follows: the hearth is exposed to heat from both sides, so that the heating chamber temperature is limited by the life of fire-clay refractories to 1800 deg. Fahr.; the entire furnace load must be borne by the hearth and piers at considerable temperature, which limits the allowable loading of tile hearths to about 70 lb. per square ft.; and the arrangement is not adaptable to car-type furnaces and most other moving-hearth types. Also, the heating capacity is limited by this construction, as has been mentioned and as will be shown later.

Overfired Type.—The overfired construction consists of a combustion chamber over the heating chamber and separated from it by means of a perforated arch, as shown in Fig. 17.

The heat of the fuel is generated in the combustion chamber and is forced down by combustion chamber pressure into the heating chamber, from which it is removed by flues in the furnace side-walls at hearth level.

The purposes of this arrangement are just the same as in the case of the underfired design, namely, to insure complete combustion before the gases reach the heating material and to prevent the direct impingement of any flame, or to obtain even distribution

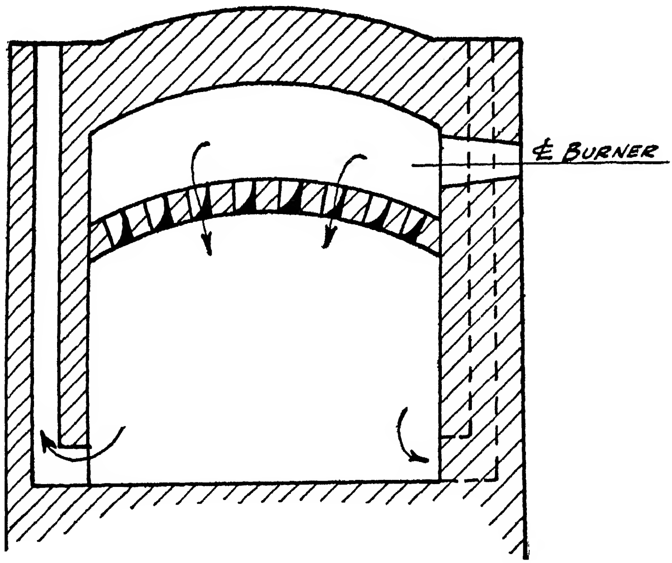


FIG. 17.—Overfired Furnace Arrangement.

of heat at low temperatures. The theory of design is the same, in that the average amount of fuel should be liberated at the rate of about 12 B.t.u. per cu. ft. per sec. and the hot gases should pass through the perforated arch at the rate of about 3 to 5 ft. per sec. The arrangement is somewhat more efficient than the underfired design, because the gases sweep through the heating material before leaving the flues at hearth level. It can be adapted to almost any form of furnace, and is not seriously limited in the capacity to be forced. However, in spite of these advantages, the overfired arrangement is not used nearly so

much as the underfired, on account of the cost of upkeep. The perforated arch is usually built of special tile and is costly in any case because of the amount of labor required to renew it, which must be done quite frequently where the heating chamber temperature exceeds 1600 deg. Fahr., or where there is any considerable vibration. The overfired arrangement is exceedingly handy where floor space is limited, but the upkeep cost will prevent it from having a wide application in spite of the extremely satisfactory results which may be obtained with its use.

Sidefired Type.—The sidefired arrangement of a furnace interior consists of a bridgewall of brick between the burners and the heating chamber. This wall promotes ignition, by checking the velocity of the fuel from the burners to a point below the maximum speed of ignition of the fuel, and aids combustion by causing a turbulent condition, so that, when the gases pass over the wall, fuel and air are intimately mixed. Also, the heating material is protected from any impingement of sharp flame. Figure 18 shows several variations in the sidefired design, sketch *a* being the common construction for furnaces not exceeding about 6 ft. in width. Over that width, the double sidefired arrangement of sketch *b* is preferable for even distribution of heat throughout the furnace. Sketch *c* is the closed sidefired design, useful for low temperatures below 1100 deg. Fahr., where the gases enter the heating chamber through slots in the cover tiles and the effect of the underfired design is closely approximated. For very high furnaces, over about 5 ft. interior height of heating chamber, the burners are frequently arranged in two rows, one above the other. The gases from the upper row of burners pass over the bridgewall, while those from the lower row pass from the combustion chamber to the heating chamber through ports in the bridgewall, as shown in Fig. 19. In almost all cases, the flues leading from the heating chamber to the outside of the furnace are located at hearth level in the burner sidewall; and in the wider furnaces flues are placed in both sidewalls to insure complete circulation of the combustion gases to all parts of the furnace interior.

There is no reason why a properly designed sidefired furnace

should consume more fuel than a direct-fired arrangement in any case (except in small furnaces—see Chapter IX), and there are many applications where it is slightly more efficient, owing to more complete combustion and better circulation of the gases. It is difficult to calculate fuel consumption with sufficient accu-

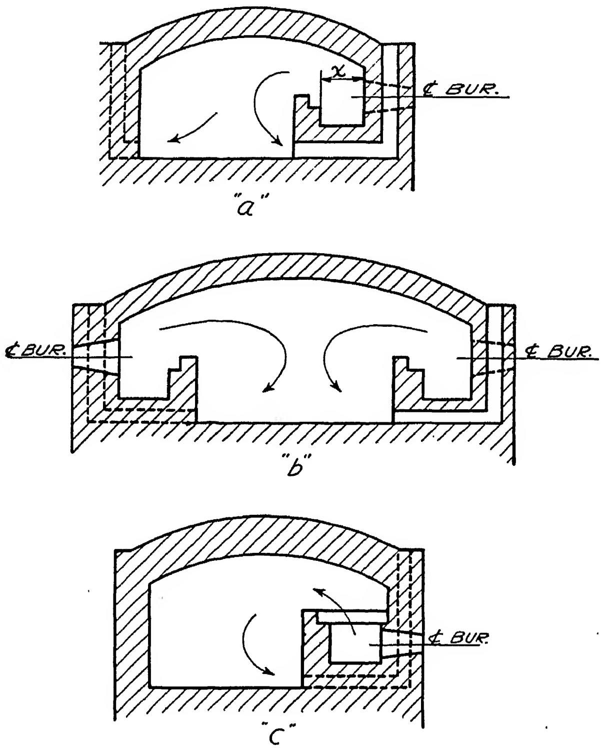
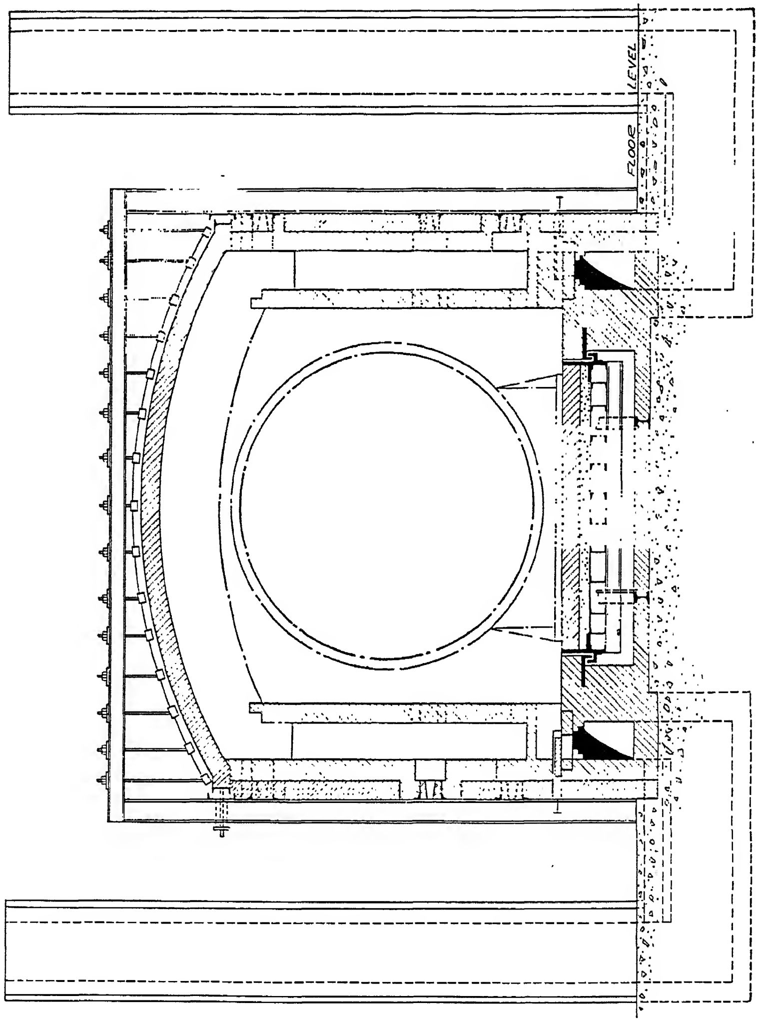


FIG. 18.—Sidefired Furnace Arrangements.

racy to differentiate between the two types, and this question should never interfere with the selection of the sidefired design.

The bridgewall should extend about $4\frac{1}{2}$ in. above the center-line of oil and gas burners, and the top course of the wall should be laid up dry, so that if the heat is found to be too confined or the flame to be thrown too high, the top course can be easily

knocked off without interfering with furnace operation. The distance between the inside of the furnace wall and the bridge-



G. 19. High

wall (X in Fig. 18) depends upon the amount of fuel burned per furnace length. Assuming that a single row of burners 3 ft. apart for average practice, the following values of

dimension X are about correct for various amounts of fuel oil burned by each burner (per 3 ft. furnace length):

Gallons Fuel Oil per Hour	Dimension X, between Inside Furnace Wall and Bridgewall, Inches
3	$13\frac{1}{2}$ to 18
5	18 to 24
10	24 to 30
15	30 to 42
20	42 to 60

These dimensions are also correct for the B.t.u. equivalents of gaseous fuels. If the bridgewall is too far from the burner, the temperature behind the wall will not be high enough to maintain efficient combustion of the fuel, while if it is too close, the wall will burn out in a short time.

The advantages of this useful arrangement of furnace interior are that it can be used with furnace temperatures up to 1900 deg. Fahr. without rapid. deterioration of refractories and frequent repairs; that the refractories are exceedingly easy and cheap to replace; that the temperature can be very accurately controlled and equalized for all furnace temperatures; and that the design can be adapted to so many material-handling arrangements. The only serious disadvantage is the width required by the bridgewall and combustion space, which is especially important with small furnaces. Since forging and forming temperatures have been reduced in recent years, the sidefired design has become more popular for this work, resulting in more satisfactory conditions, so far as oxidation of work is concerned, than are possible with the direct-fired design which was formerly used. Side firing is as necessary with gas as with fuel oil in order to obtain maximum temperature uniformity and minimum oxidation.

Direct-fired Type.—In this design, the fuel is simply fired into the furnace without striking any sort of baffle. The source

of heat may be located at either the sides or ends of the furnace, as is also true for the preceding arrangements, and the flue gases are removed through flues in the roof, sidewalls, or hearth of the furnace. Figures 20 and 21 show several common arrangements. The design of Fig. 20*a*, which may be successfully used for fur-

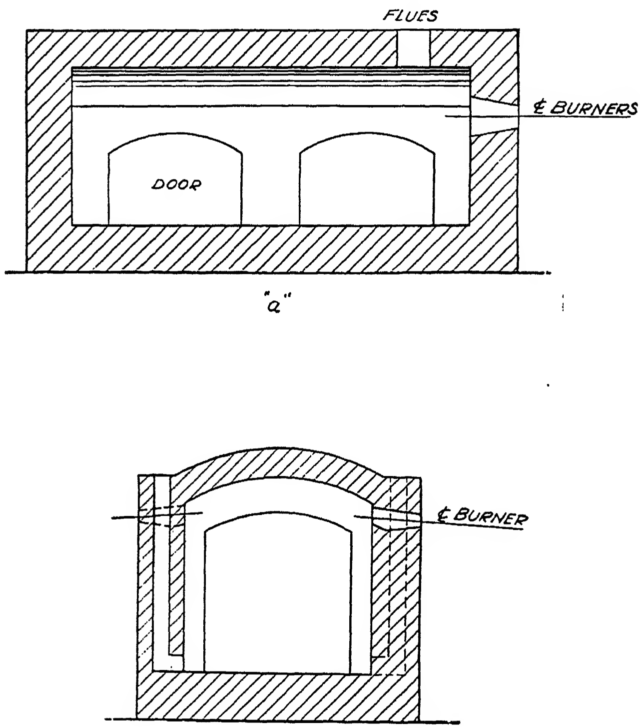


Fig. 20.—Direct-fired Furnace Arrangements.

naces up to 10 ft. in length, consists in locating the flues in the roof directly above the burners, which are concentrated at one end. The force of the oil or gas flame from the burners carries it past the flues, and the flue gases cannot escape (except through leaky doors) until they have traveled back across the hearth. The burner flame entrains part of these gases and carries them around again, resulting in good heat utilization. The life of the

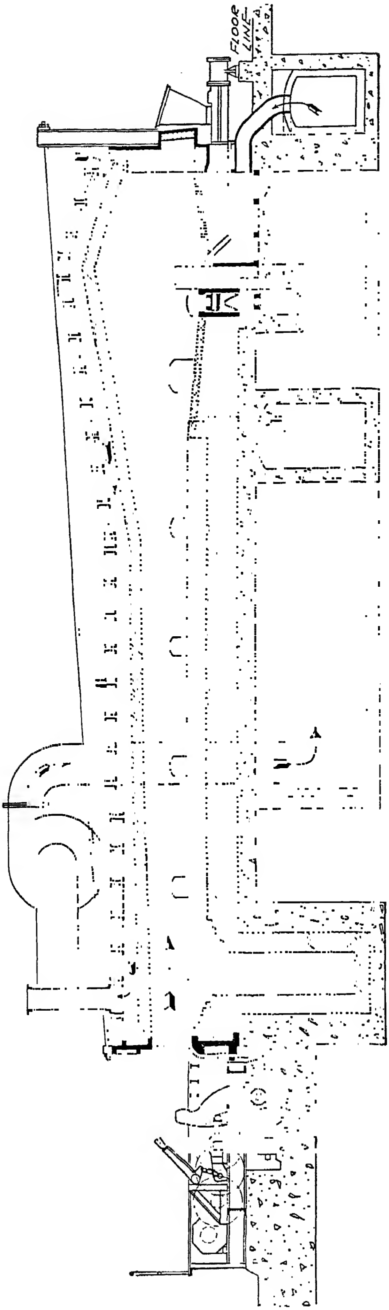


FIG. 21.—Coal-fired Billet Heating Furnace.

refractories is long, because the walls are not honeycombed by flues. Figure 20*b* shows a section of a typical long furnace of narrow width in which the burners in the two sides are staggered throughout the length, and the flues are in the walls between burners. Figure 21 is a form of the common high-temperature continuous billet-heating furnaces, where the flue gases are pulled by stack draft through a downtake outlet flue in the hearth.

Powdered coal is usually fired directly into the furnace, but other forms of coal are never strictly direct-fired, because a bridgewall is always required to retain the fuel bed. Electric furnaces are a form of direct firing, but are entirely different from fuel-fired furnaces in that there is no flame to strike the heating material and there are no gases to be removed.

The direct firing of furnace fuels produces a high velocity of gases with consequent rapid heat transfer, and the radiant

power of the flame is completely utilized. Fairly complete combustion can also be obtained by proper design, but for furnaces under 1800 deg. Fahr., temperature control is exceedingly difficult because of the great difference between the flame temperature required for combustion and the temperature desired for the heating material. Above 1800 deg. Fahr., these temperatures are more nearly equal, and radiation assists in equalizing the furnace temperature.

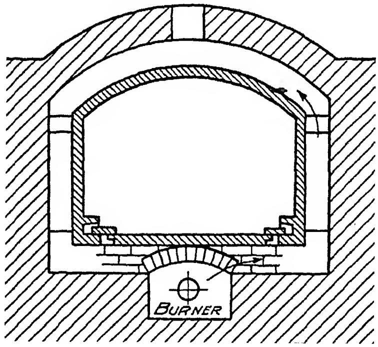


Fig. 22.—Material-muffled Furnace Arrangement.

The advantages of the direct-fired design are the long life of furnace refractories and the high temperatures possible with this long life, while the disadvantages are the difficulty in obtaining even temperature distribution and the tendency to scaling of heated stock.

Muffle Type.—This type of furnace may be one of two general designs. In one, the heating material is muffled and the flame or heat applied on the outside of the muffle, and in the other the flame is muffled and the heat radiated from the outside of the muffle to the heating material in the furnace. The two arrangements are shown in Figs. 22 and 23, which are common arrangements where muffling is required, although there are many such as the rotary metallic drum design. The con- in which the material is muffled is the oldest type, and

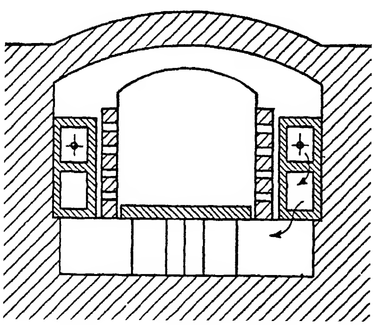


Fig. 23.—Flame-muffled Furnace Arrangement.

there are many of these furnaces in use for such processes as enameling, where impurities in combustion gases would cause discoloration or other injury to the work. The use of this arrangement was first challenged by the electric furnace, which has no gaseous products to do injury, and later by the muffled flame arrangement of Fig. 23, which has much the same characteristics as an electric furnace and can utilize cheaper fuels.

Radiation losses are less in the carboradiant design of Fig. 23 because in the simple muffle of Fig. 22 the temperature on the outside must be high in order to force the heat through the muffle, with the result that radiation is high from the outside furnace walls. Also, there are mechanical advantages in the construction of the smaller carboradiant muffles, but the furnace size is greater, a circumstance which partially offsets the chances for exceptional fuel economy. Some idea of the necessary temperature difference through a muffle such as that of Fig. 22 can be had from a comparison with an equivalent electric furnace. Most electric furnaces are limited to about 3 KW-hr. developed per square foot of resistor-covered wall, roof, or hearth, which corresponds to 3×3415, or 10,245 B.t.u. per sq. ft. per hour. The average conductivity of carborundum at furnace temperatures is about 70 B.t.u. per sq. ft. per hour per deg. Fahr. per in. thickness, and muffles are about $1\frac{1}{2}$ in. thick, so that the effective heat transfer is about 46.7 B.t.u. per sq. ft. per hour per deg. Fahr. To pass an amount of heat equivalent to that passed by the electric furnace, the temperature difference between the outside and the inside must therefore be about $\frac{10245}{46.7} = 220$ deg. Fahr. Muffle furnaces can be direct-fired outside the muffle because the high conductivity of the muffle material serves to equalize rapidly the temperature throughout the muffle surface.

In the design of the muffled flame arrangement, the muffle is made of carborundum about $1\frac{1}{2}$ in. thick and is arranged either in single pass, in which the heat is fired in at one end and leaves at the other, or in double pass, where the gases return through the muffle at a different elevation and leave at the end into

which the burner fires. In either case, the gases are usually carried under the furnace floor in order to give up as much of their heat as possible before leaving the furnace. It is possible to burn from ½ to 2 gal. of oil per cubic foot of muffle when using burners with which part of the air is induced, and from 1 to 2½ gal. when all combustion air is supplied under pressure. Greater proportional amounts can be burned in smaller chambers, which vary in size from about 4 by 6 in. by 15 ft. maximum length to 12 by 18 in. by 40 ft. maximum length. The high conductivity of most muffle materials equalizes the muffle temperatures throughout their length. The fuel consumption in any type of muffle is higher than in any of the previously mentioned furnace designs because of the greater difference in temperature required on one side of the muffle to force heat through it.

Application of Types to Common Furnaces

Before considering the actual application of the above methods of heat application, let us see what important heating processes require the use of industrial furnaces, and what the essential requirements of the processes are. Classified according to temperature requirements, the following table shows the principal processes found in industrial plants which require furnaces for the heat treatment of steel.

Temperature, Deg. Fahr.	Processes
0– 300	Tempering of hardened steel.
300–1000	Tempering of hardened steel, core ovens.
1000–1350	Tempering, quenching of high-speed steel, preheating, annealing.
1350–1700	Hardening, annealing, case hardening, carburizing, cyaniding.
1700–1900	Hardening, annealing, case hardening, carburizing, heating for bending and forming.
1900–2200	Heating for forming, drop forging and pressing, hardening of high-carbon steel, annealing of alloy steels.
2200–3000	Heating for forging and rolling.

Definitions.—Further definitions of the heat-treatment terms used in furnace design are as follows:[1]

Hardening.—Heating and quenching certain iron-base alloys from a temperature either within or above the critical temperature range.

Annealing.—Heating and cooling operation of material in the solid state. The purpose of such treatment may be:

(*a*) To remove stresses.
(*b*) To induce softness.
(*c*) To alter ductility, toughness, electrical, magnetic, or other physical properties.
(*d*) To refine the crystalline structure.
(*e*) To remove gases.

In annealing, the temperature of the operation and the rate of cooling depend upon the material being heat treated and the purpose of the treatment.

Normalizing.—Heating iron-base alloys above the critical temperature range, followed by cooling to below that range in still air at ordinary temperatures.

Tempering (also termed Drawing).—Reheating after hardening to some temperature below the critical temperature range, followed by any rate of cooling. Tempering temperatures, if not maintained for an excessive length of time, are approximately indicated by the color of the steel, and these colors are as follows:[2]

	Deg. Fahr.
Faint yellow	430
Straw yellow	460
Dark straw	470
Purple	530
Blue	550
Full blue	560
Pale blue	600
Black; red visible in the dark	752

[1] These definitions were drawn up by a committee of the American Society for Testing Materials, The Society of Automotive Engineers, and the American Society for Steel Treating. They were tentatively adopted by the A.S.T. M. at its convention, June 20, 1927.

[2] These data not included in the report referred to above.

Graphitizing.—A type of annealing of cast iron whereby some or all of the combined carbon is transformed to free or uncombined carbon.

Carburizing (*Cementation*).—Adding carbon to iron-base alloys by heating the metal below its melting point in contact with carbonaceous material.

Case Hardening.—Carburizing and subsequent hardening by suitable heat treatment of all or part of the surface portions of a piece of iron-base alloy.

Cyaniding.—Surface hardening of an iron-base alloy article or portion of it by heating at suitable temperature in contact with a cyanide salt, followed by quenching.

With the above temperature outline in mind, we can now consider these groups in the order given, and see which methods of heat application are best suited in each case, and the factors which determine the type of furnace selected. As previously stated, the classification according to methods of material handling will be discussed in the next chapter, and will not be considered in the following discussion.

For the range from zero to 300 deg. Fahr., the oven or open type of furnace is seldom used, and most furnaces for this temperature used in the treatment of steel are of the oil-bath construction, where the oil used as a heating medium is contained in a cast-iron pot heated from the outside. The steels tempered at these low temperatures are special, and the pieces to be heated quite small, so that the maximum size of pot ordinarily used is about 2 ft. by 3 ft. by 2 ft. deep. Since the amount of fuel required is small, it is burned in a very small combustion chamber within the furnace into which the pot is built, so that the actual combustion temperature may be high but the amount of hot gases produced small. Tempering is the process of reducing the extreme hardness and brittleness of steel that has been hardened. The exact attainment of a certain hardness depends upon control of the tempering temperature; temperature control must therefore be very accurate.

The range of temperature from 300 to 1000 deg. Fahr. also usually means a tempering operation, but it includes the tempering of common steels, which is done in very large quantities

and with some allowable variation in accuracy. The selection between pot furnaces and oven furnaces depends upon these two features. The pot furnace, in which special liquid salts are usually used as heating mediums, is ideal for tool steels and other high-carbon steels or alloy steels, because of the clean surface produced and the extremely accurate temperature control, as well as for medium-carbon steel parts of small size, such as automobile steering knuckles. For large-sized pieces of medium-carbon steel made in large quantities, the size of the pot required and the large number of pots make the oven type of furnace more desirable. Furnace pots are usually of cast iron for these temperatures, and the furnace construction is the same as described in the last paragraph, with the combustion chamber separated from the pot chamber by surrounding brickwork and of such a size as to suit the amount of fuel required. Figure 24 shows in detail an arrangement for maintaining ignition temperatures in a low-temperature oil-bath tempering furnace. Maximum pot sizes are generally the same as previously given for low-temperature oil-bath furnaces. On account of the low temperature, the underfired, overfired, or closed sidefired designs are the only arrangements suitable for oven-type furnaces in this group. All three are excellent, and the choice depends upon the mechanical construction of the furnace. The size of oven furnaces for this range may vary from small portable furnaces to large continuous furnaces of almost any desired dimensions.

The range from 1000 deg. to 1350 deg. Fahr. begins to include a large variety of heating operations. One is the tempering of special steels requiring high temperatures, and the considerations are the same as in the furnaces just described. Another is the quenching of very high-grade steels in a pot furnace containing salts at these temperatures, to produce hardness but prevent breaking, warping, and cracking, which would accompany the quenching of these steels in cold liquids. Still another is the preheating of steel parts in either pot furnaces or oven furnaces in preparation for rapid heating in hardening salts or lead pot furnaces. This preheating is necessary to prevent sudden strains. Probably the largest number of furnaces in this range

are those used for annealing of heat-treated parts or castings. The oven type of furnace is generally used for this annealing, and again the design depends upon the size and mechanical arrangement. The underfired design is almost always used for small

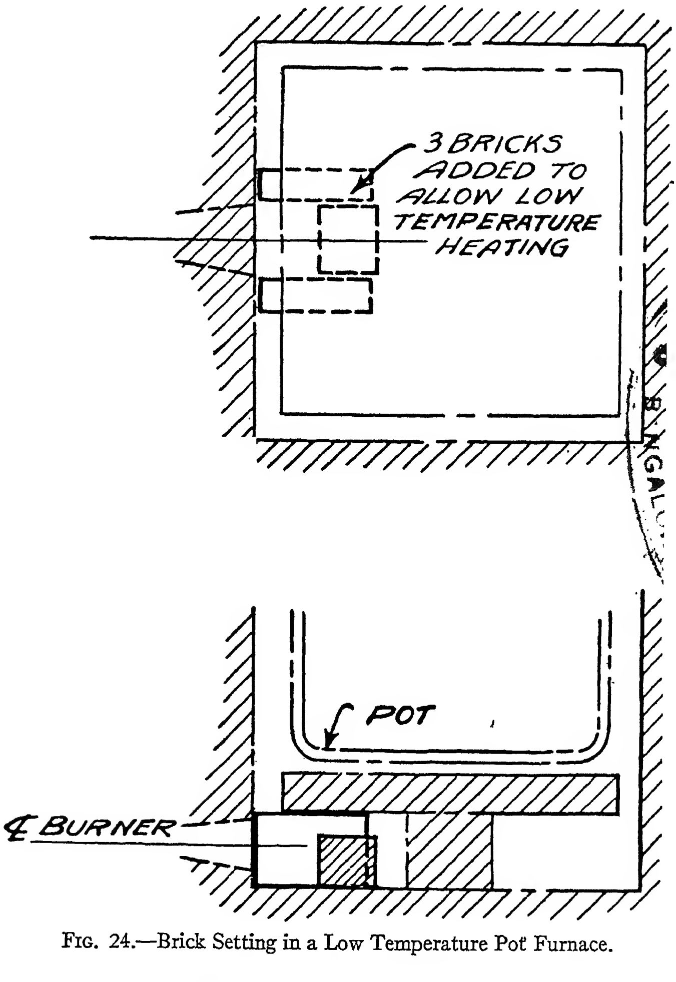


FIG. 24.—Brick Setting in a Low Temperature Pot Furnace.

furnaces under a width of 4 ft., such as that shown in Fig. 25, while the overfired or closed sidefired arrangement is best for larger furnaces, which may be any size within possible construction limits.

The temperatures from 1350 to 1900 deg. include the majority of industrial heating furnaces, and almost all possible kinds are built for these temperatures. They may be conveniently divided into pot furnaces, portable oven furnaces, and large oven furnaces. In the pot furnaces, high-temperature salts or lead are

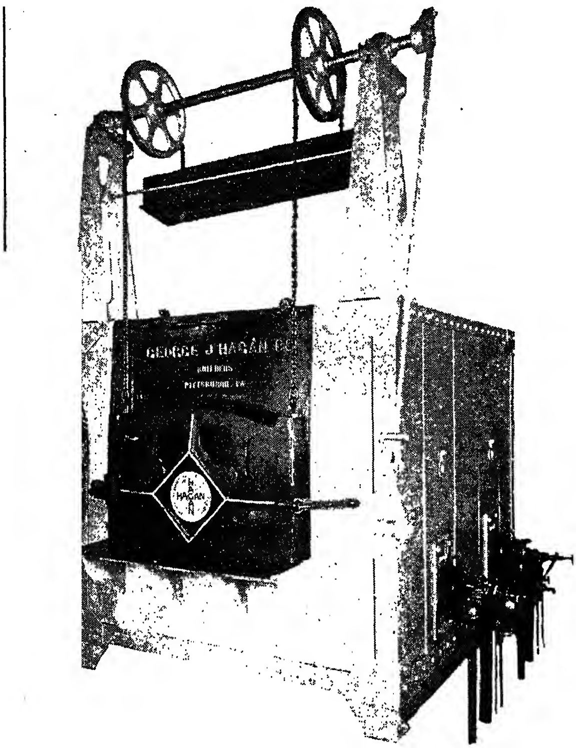


FIG. 25.—A Portable Underfired Furnace.

used as heating mediums, and the process is generally cyaniding, where the steel is heated above the critical point and quenched in water or oil to obtain hardness. For this high-temperature work the pot furnace is used because of absence of oxidation of pieces heated, rapidity of heating due to high rate of heat transfer from

liquid to metal, and uniformity of heating of material in liquids, and because warping and cracking are not so common at these temperatures in a liquid bath. Also, part of a piece may be hardened without affecting the remainder, which in many cases is a real factor, because it is sometimes desired to harden one portion before machining the remainder. This may be accomplished by immersing only the desired portion in the heating liquid. Pots for these temperatures are of cast steel, pressed steel, or alloy. The selection of the most suitable material is always a matter for experimental determination because of the extreme variation in conditions, but any of the materials used will have a good life if good salts are used and if the pot is protected from the cutting action of flames on the outside. The size of the pot depends upon the amount of liquid required. One company states that, for their material, good rules to use are that at 1500 deg. Fahr. the weight of the steel charged equals one-tenth of the weight of salt in the bath, or that the weight of steel heated per hour equals three-tenths of the weight of salt in the bath. The cost of heating for the pot furnace often compares favorably with that for the oven type, and is dependent upon first cost of equipment, fuel consumption, and salt or lead consumption, in addition to the character of the work obtained.

The theoretically proper construction of pot furnaces is to have the heat from a separate combustion chamber strike the top of the pot and be vented at the bottom of the furnace, but this is a complicated arrangement for small pots and the result is hardly worth the effort. Good results can be obtained with the fuel fired beneath the pot, which is protected from direct impingement by a refractory shield under the pot. The burners should be so arranged that the gases circulate as much as possible around the pot before venting at the top. Figure 26 shows a typical standard circular pot furnace. Some useful data on the approximate physical properties of some liquid heating mediums are shown in table 8.

The portable oven furnaces include those for hardening dies, high-carbon steels, and ordinary steels, and those for annealing steel and cast-iron parts of comparatively small size. They are

TABLE 8

PROPERTIES OF LIQUID HEATING MEDIUMS

	Lead	Low-temperature Salts	High-temperature Salts	Salts for Case Hardening
Operating temperature range, deg. Fahr.	650–1550	1000–1350	1300–1700	1200–1600
Average liquid loss in operation, pounds of liquid per 100 lb. steel heated	0.50*	0.50	0.70	0.50
Density, pounds per cubic foot (liquid)	710	127	159	107
Average specific heat, B.t.u. per pound	0.03	0.25	0.17	0.34
Heat of fusion, B.t.u. per pound	10.06	90 to 180		
Melting point, deg. Fahr.	620	950	1200	1050

* With lead, one pound of charcoal covering is also required per hour per square foot of bath surface.

usually of the underfired construction except in the case of some continuous arrangements. The large oven furnaces for these temperatures are used for all sorts of hardening and annealing operations; carburizing, where the steel is packed with carburizing compound in a metal container and sealed for heating 8 to 12 hours to produce a deep surface case hardening; heating for bending, as for plates, pipe, and structural material; and rolling, in the case of thin sheets. The underfired and overfired constructions are seldom used except where the mechanical construction of the furnace makes them desirable, and the sidefired is by far the most common and the best arrangement for almost any sort of work at these temperatures. It should always be used wherever possible in preference to the direct-fired arrangement. Muffle furnaces for enameling are also included in the range of temperature from 1350 to 1900 deg. Fahr., as are rotary metal muffle furnaces for hardening, annealing, and carburizing of small parts. High-temperature enameling, porcelain enamel-

ing, and vitreous enameling are different terms for the general process which includes the following:

Wet enameling of cast iron: stove parts, refrigerator parts, etc.

Wet enameling of sheet steel: stove parts, table tops, reflectors, signs.

Dry enameling of cast iron: bath tubs and other sanitary ware.

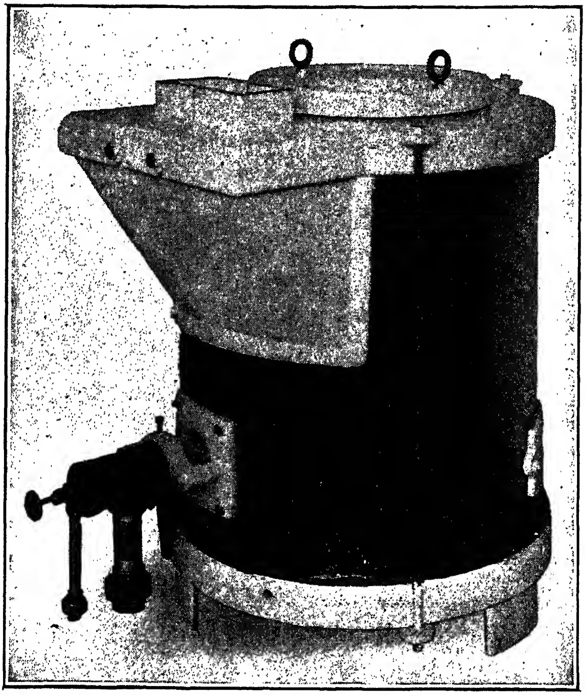


FIG. 26.—A Circular-pot Furnace.

Except for annealing of stainless steel, hardening high-speed and alloy steels, and a few other processes, the furnaces for temperatures between 1900 and 2200 deg. Fahr. are all for the purpose of heating steel for forming, drop forging, pressing, and similar operations. The number of such furnaces in this range is increasing with the trend toward greater strength in forming

machinery designed to form pieces at lower temperatures with consequent greater strength. Small underfired furnaces with carborundum hearths and linings are commonly used for high-speed steel and die hardening, while the furnaces for forming are best suited to the sidefired or direct-fired arrangements. The sidefired is the best in most cases if care is taken that there is ample combustion space and plenty of space over the bridge-wall, but most of the furnaces now in operation are of the direct-fired design, which means that there is more oxidation of work and less uniformity of temperature, with consequent greater wear on forming machinery, than there should be. The temperatures are entirely too high for underfired or overfired furnaces of any size, because the combustion chamber temperature must be greater than these temperatures and the refractory is exposed to this intense heat on both sides.

Except in the case of coal-fired furnaces, where the grate is separated from the heating chamber by a bridgewall, the direct-fired design is the only type suitable for temperatures above 2200 deg. Fahr., which include furnaces for forging ingots and large pieces and for heating billets for rolling. These furnaces are always direct-fired, and, with proper design, very uniform temperatures are secured, because radiation is very active above 2200 deg. Fahr. and tends to equalize the temperature. Also, the flame temperature is very little higher than the actual furnace temperature, as explained previously. Furnaces for these temperatures are seldom of portable construction, but are large and ruggedly built on heavy foundations. A luminous, reducing flame is generally maintained in the furnace to keep oxidation of the material being heated to a minimum, although this action cannot be entirely eliminated because steel has a greater affinity for oxygen than has commercial fuel, so that, even with perfect combustion, the gases will break down to some extent and give up some of their oxygen to form scale.

Furnace Capacity and Size

The three main considerations in the determination of the general type of furnace best suited to certain definite require-

ments are application of the heat of the fuel, mechanical handling of the heating material, and the furnace capacity and size required. All of these are definitely interconnected and must all be considered simultaneously in the determination of furnace type. Having seen the various factors influencing the selection of the best method of applying heat, we shall next consider furnace size, before studying the question of material handling, which will be taken up in the next chapter. Let us now see how the capacity of a furnace is determined.

The factors determining the size of an industrial heating furnace are (1) The amount of material to be heated per unit of time, (2) various sizes of pieces to be heated and heating time necessary for the desired heat treatment, and (3) heating rate possible with the furnace arrangement selected.

Taking these up in the order named, the first factor is extremely flexible and variable, and its accurate determination requires the knowledge of such data as whether the supply of material is steady or intermittent, maximum and minimum probable amounts of material, and all similar information. In most plants it is customary to refer to the desired production as so many pounds of steel, or so many pieces per day. The furnace designer must then find out in how many hours this amount must be heated, whether the supply of material to be heated will be fairly constant over this period, and, if not, what maximum production will be reached in maintaining this average. These data sometimes require somewhat tedious investigation, but it is always well worth while because unsatisfactory and even disastrous results commonly arise from an incorrect analysis of this question, since a furnace that is too large can be very inefficient, while one that is too small must be forced, and usually has a short life and high upkeep cost. Industrial furnaces are rated on the pounds of steel heated per hour, and the best practice is to determine carefully in every case the average weight of material to be heated per hour, the minimum and maximum rates, and the percentage of time during which these rates will prevail. Then, from a consideration of these figures, the size can be so fixed that the furnace will be working at its most effi-

cient rate for the greatest amount of time that will, at the same time, allow the maximum production to be taken care of when necessary.

The heating time required depends on the dimensional size of the piece and the metallurgical requirements of the process. The rapidity with which any material can be heated depends, first, on the conductivity of the material, which is independent of the temperature of the heating medium, so that the outside of a piece may be melting while the center is still dead cold. This fact is not always fully appreciated and accounts for many broken dies and rolls and unevenly heat-treated parts. For steel, the time required to heat thoroughly can be satisfactorily determined from such rules as twenty minutes per inch of diameter for round sections, and $\frac{1}{8}$ in. penetration of heat in five minutes for flat sections.[3] The other factor upon which the heating time is dependent is the rate of heat transfer from the heating medium to the material, which is dependent upon the temperature of the heating medium. Which of these is the determining factor in any case depends upon the furnace temperature, and, ordinarily, at temperatures above 1400 deg. Fahr. it is the conductivity, while below that temperature it is the rate of heat transfer. The rules given above are for temperatures above 1400 deg. Fahr., and can be corrected for lower temperatures by multiplying by 2 for temperatures between 800 and 1400 deg. Fahr. and by 3 for temperatures below 800 deg. All these figures are for oven furnaces. With liquid baths, the rate of heat transfer is greater, and the heating time is limited by conductivity over almost the entire temperature range. Any additional heating time, such as "soaking" (holding the material at its final temperature for a period of time) or other metallurgical requirements must be determined by the metallurgist.

Knowing the pounds of material to be heated per hour and the individual weight of pieces, one can readily determine the number of pieces to be heated per hour. Then, from the heating

[3] *Industrial Furnaces*, Vol. I, by W. Trinks. This text also gives rules to be used for other materials.

time required for each piece, the number of pieces which must be in the furnace at any one time is determined by multiplication. For example, a furnace to heat 120 pieces per hour for one-half hour each would have to hold $\frac{1}{2} \times 120$, or 60 pieces at one time. Knowing the size of the pieces, and the number which may be piled on top of each other without interfering with proper heating, one can easily determine the hearth area required to hold the pieces.

The area so obtained must now be checked by consideration of the third and last factor, heating rate possible with the furnace arrangement. By this is meant the amount of heat, expressed by the amount of steel heated per square foot of hearth area per hour, which may be liberated without injury to the furnace brickwork. This rate varies for the different interior arrangements, but if the pounds of material per hour heated per square foot of hearth area, obtained by the above method, do not exceed 35 lb. for underfired furnaces, 50 lb. for overfired furnaces, 70 lb. for sidefired furnaces, and 100 lb. for the direct-fired arrangement, the furnace will operate satisfactorily. These figures apply only to thorough heating, without soaking, and can be exceeded 10 to 20 per cent, but only at the expense of somewhat shortened refractory life. If it is found by this method of checking that the furnace is not large enough, it should always be made larger, with correspondingly longer heating time of the material resulting. If it is too large, it can sometimes be made smaller by a different piling or arrangement of the material in the furnace. The effect of muffles on allowable heating rate may be judged from the fact that muffled enameling furnaces are operated at a rate of about 25 lb. per sq. ft. per hour for enameling cast-iron pieces, and of 18 to 25 lb. for sheet enameling.

The allowable rates given above are for heating mild carbon steel; for other materials the rate of heating (and actual heating time) depend upon the ratio between conductivity $\times$ density for carbon steel and conductivity $\times$ density for the material in question. For brass, the rates may be multiplied by 2.0; for copper, by $2\frac{1}{2}$; for alloy steels, $\frac{3}{4}$; and for aluminum, 1.15.

These ratios were calculated from data included in Table 9 of useful physical properties:

TABLE 9

PROPERTIES OF METALS

	Conductivity, B.t.u. per Square Foot per Hour per Deg. Fahr. per Foot Thickness	Mean Specific Heat for Range from Zero to Melting Point	10,000 × Coefficient of Linear Expansion per Deg. Fahr.	Melting Point, Deg. Fahr.	Density, Pounds per Cubic Foot
Mild carbon steel	34	0.165	0.063	2530	488
Alloy tool steel..	26	0.175	....	2700	481
Brass..........	63	0.100	0.104	1645	530
Aluminum......	116	0.247	0.128	1214	165
Nickel.........	33	0.108	0.071	2640	549
Cast iron.......	28	0.110	0.059	2200	450

As an example of the use of the ratio between the product, conductivity × density, for mild steel and for other materials, it is possible to anneal brass at the rate of 2.0 × 35 = 70 lb. per sq. ft. of hearth per hour in an underfired furnace.

Examples of size determination: *Example I.*

Suppose that a furnace is to be designed for heating billets to a temperature of 2300 deg. Fahr. for rolling at the rate of 200 short tons per day of finished structural shapes. Investigation of mill practice discloses the fact that there is a 10 per cent mill loss in rolling, resulting from scale, crop ends, and other waste, so that the tonnage actually heated per day is about 220 tons. The working time of the furnace is to be 10 hours per day, which means that an average of 44,000 lb. of material must be heated per hour. But the tonnage rolled per hour will vary, on account of breakdowns and other delays, so that a maximum rate of 80,000 lb. per hour will be reached for two or three hours each day. From these data, we can determine the production for which to design the furnace at about 50,000 lb. per hour, as the less efficient overload rates are for comparatively small percentages of the total time and the operations are likely to be fairly steady during most of the day.

The billets are 4 by 4 in. by 20 ft. long, which would appear to require a heating time of about 90 minutes (80 minutes for 4 in. diameter round on basis of 20 minutes per inch diameter). The weight of each billet is 960 lb., so that $\frac{50{,}000}{960}$, or 52 billets per hour are to be heated. The number that must be in the furnace at one time will then be:

$$1\tfrac{1}{2} \text{ hours} \times 52 = 78 \text{ billets.}$$

Assuming that the furnace is of continuous design (Fig. 21) with each billet pushing the preceding one through the furnace, each billet will require 4 in. furnace length, and the total hearth length will be:

$$\tfrac{1}{3} \times 78 = 26 \text{ ft.}$$

Allowing 22 ft. in width for 20-ft. long billets, the hearth area is:

$$26 \times 22 = 572 \text{ sq. ft.}$$

The pounds heated per hour per square foot of hearth area then average:
50,000
87.5.

This figure is too high, because at the maximum production the rate will be:

$$\frac{80{,}000}{572} \quad 140 \text{ lb. per sq. ft. per hour,}$$

which is too much greater than the allowable 100 lb. for a direct-fired furnace. Also, as explained later under the discussion of fuel consumption, this type of furnace is more efficient when operated at an average rate of about 50 lb. per sq. ft. per hour; it would therefore be better to make the hearth area:

$$\frac{50{,}000}{50} = 1000 \text{ sq. ft.}$$

which means a hearth length of:

$$\frac{1000}{22} \quad 45 \text{ ft.,}$$

and a heating time for the billets of

$$\frac{45}{26} \times 90 = 156 \text{ minutes} = 2.6 \text{ hours.}$$

The discrepancy between this and the assumed heating time is due to the fact that the billets in a continuous furnace are not exposed to high temperature for the first part of their journey through the furnace, and

therefore heat transfer is less than conductivity, and the rule based on conductivity does not hold.

The agreement between the result obtained and the check result for hearth area is usually quite close, but this example shows the advantage of carrying through the entire process of calculation, instead of simply assuming a figure of 50 lb. per sq. ft. per hour in the first place. It is always better to carry through the above method of calculation in every case, because all variations, such as size-weight relations of the pieces to be heated, are then taken into consideration, and because there is a valuable check on the calculations.

Example II.

Suppose that it is desired to design a furnace for heating round steel bars to 1900 deg. Fahr. for forging. The bars will be 2 in. in diameter and 36 in. long, and are to be heated at a rate of 30 bars per hour. The furnace will be sidefired and of ordinary batch-type construction, the operation being to charge a cold bar to replace each heated bar withdrawn for forging.

On the basis of 20 minutes per inch of diameter, the heating time required will be:

$$2 \times 20 = 40 \text{ minutes, or } \tfrac{2}{3} \text{ hour.}$$

The number of bars in the furnace at any time will then be:

$$\tfrac{2}{3} \text{ hour} \times 30 \text{ bars per hour} = 20 \text{ bars.}$$

Allowing 3 ft. 6 in. hearth depth to take the 36-in. long bars, and a 1-in. space between bars in the furnace, the hearth required will be:

$$3\tfrac{1}{2} \text{ ft.} \times 5 \text{ ft.} = 17.5 \text{ sq. ft.}$$

The weight of each bar is 32.8 lb., and, checking the heating rate, we have:

$$\frac{30 \text{ bars/hour} \times 32.8 \text{ lb.}}{17.5 \text{ sq. ft. hearth area}} \quad 56.2 \text{ lb./sq. ft. per/hour.}$$

Since 70 lb. per sq. ft. per hour is allowable with the sidefired design, this check indicates that the furnace could be made shorter, with less than 1 in. allowed between bars, but for ease in handling the bars in and out of the furnace and to give the refractories every chance for a long life, the dimensions as originally determined are just about correct.

Example III.

Let us assume that an annealing furnace is required to anneal plain gears at a temperature of about 1600 deg. Fahr. The gears have an average diameter of 14 in., and a weight of 45 lb. The production required is 12 gears per hour, and they can be most satisfactorily heated in an underfired batch-type furnace. The heating time required has been found from experience to be 1 hour. The gears in the furnace at any time will be:

$$1 \text{ hour} \times 12 \text{ gears per hour} = 12 \text{ gears.}$$

Figuring on a double-end furnace (doors at both ends) and two rows of gears in the furnace, the required hearth will be 36 in. wide and 7 ft. long inside the door jambs, and the hearth area will be:

$$3 \times 7 = 21 \text{ sq. ft.}$$

Checking the heating rate, we find that it is:

$$\frac{12 \text{ gears/hour} \times 45 \text{ lb. each}}{21 \text{ sq. ft. hearth area}} = 26 \text{ lb./sq. ft./hour.}$$

This heating rate is correct for the underfired construction. In the case of ring gears, where a gear of this diameter weighs only about 15 lb. but must heat evenly and in a flat position, and one gear must not be piled on another, the rate will be only about 10 lb. per sq. ft. per hour, and the efficiency must suffer. This is another example of the desirability of carrying out the complete calculation.

In the next chapter, the effects of various methods of material handling will be discussed, and an attempt will be made definitely to connect the three major considerations (heat application, size, and material handling) which have been outlined above, and which determine the most suitable form of furnace for specific conditions.

METHODS OF MATERIAL HANDLING

It was stated in the last chapter that after the proper fuel has been selected the question of the best furnace to utilize this fuel resolves itself into three initial and principal considerations: capacity and size, method of heat application, and arrangement for handling the heating material. These three factors are all definitely interconnected and must be considered simultaneously in the determination of the furnace best suited to the conditions to be met. The preceding chapter discussed the first two of these factors. The various furnace arrangements were described, and the application of each type to the furnaces for the common heating processes were considered. The principles and rules for the determination of furnace capacity and size were also outlined.

It remains, then, in this chapter, to study the third factor, material handling, and to see how the three factors should be considered in the selection of a suitable furnace. First we shall see the various methods available for material handling, and their application to furnaces for various temperatures and processes. We can then analyze the factors affecting the selection of any one type for particular conditions, and study how the conflicting questions of size, heating efficiency, and labor economy can be satisfactorily answered in one furnace for any set of conditions.

Methods of Handling Material in Furnaces

The methods of handling material through a heating furnace may be conveniently classified under the following principal arrangements: batch type, pusher type, car type, rotating-

hearth type, chain-conveyor type, roller-hearth type, moving-hearth type, and rotary-muffle type. There are infinite variations of each design, but most heating furnaces will fall under one of these main headings. Each arrangement has its advantages and limitations, particular suitability with different methods of heat application, and peculiar structural problems, all of which we can examine in some detail. The different types are arranged in an approximate order of simplicity; and in the selection of a suitable method of material handling for any conditions the various types should be favored in this same order, because complication in furnace design can be extremely expensive in upkeep cost. Each type should be made to prove itself satisfactorily on paper to be better in economy and operation than a simpler arrangement before it is seriously considered.

Batch Type.—Batch-type furnaces are those in which the material to be heated remains in the same position during the time that it is heated, since it is simply put into the furnace and removed when ready. The common box-type furnace is the simplest type, but there are countless variations, depending upon the method of firing, temperature, and method of operation. All methods of firing and the whole range of temperatures are represented by batch-type furnaces, and the different methods of operation depend upon the size and shape of the heated pieces and the treatment required. Very small pieces are usually handled in pans, because the extra fuel required to heat these pans is not so great as the labor required to handle the pieces separately. The furnace is generally loaded with pans, which are all withdrawn at one time, when the heat has been run. For medium-sized pieces, this method of *true batch* operation is followed for such pieces as dies, gears, etc., which require accurate heat treatment, and for those processes, such as annealing and hardening of axle shafts, in which the treatment (machining, etc.) following heating can be done in batches. Examples of true heating of large pieces are heating of very large forging ingots and the enameling of large articles. Figure 27 shows a large piece bricked into the door of a furnace, where it remains for several hours until the end is hot enough to be formed under

a forging hammer. The ingot is handled in and out of the furnace by means of chain slings supported from above. Figure 28 shows an electric enameling furnace. The article to be enameled is carried into the furnace by the charging fork shown in the foreground, and is set on piers inside the furnace. When the operation is finished, the fork again enters the furnace,

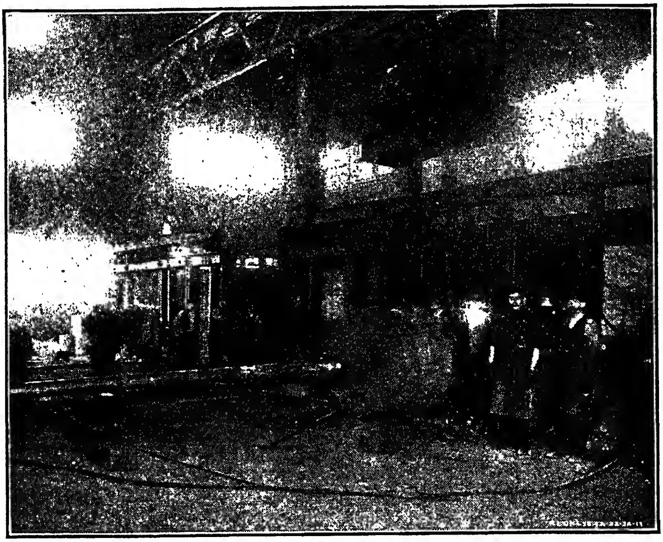


FIG. 27.—Batch Heating of a Large Piece, Showing Method of Handling.

between the piers, lifts the article, and carries it out of the furnace.

When a number of pieces of material are to be heated in preparation for a forming operation or other process requiring immediate attention when each piece is withdrawn from the furnace, the true batch operation is not satisfactory, and the pieces must be delivered one at a time by following a *continuous batch* operation. With this method, each hot piece withdrawn is replaced by a cold piece, and although various schemes of operation can be worked out, the usual method is to work the furnace from one side to the other, always leaving a blank space between the cold piece charged and the hot piece to be next

withdrawn, so that the chilling effect of the cold piece will not affect the hot one. This method of operation is sometimes

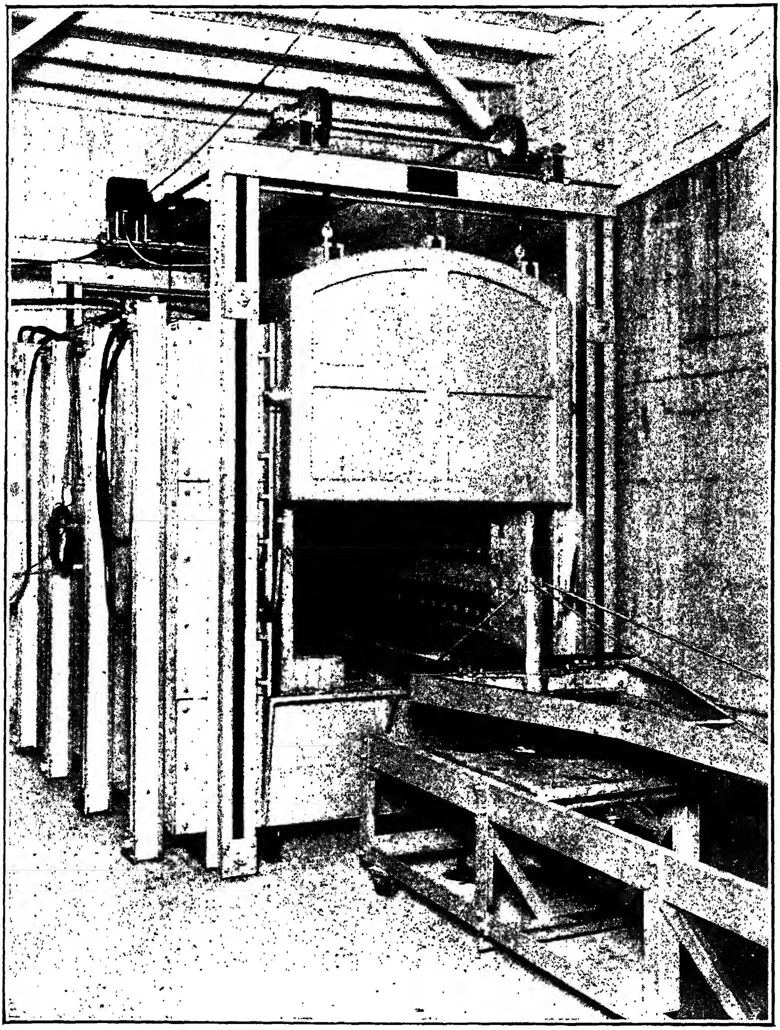


FIG. 28.—Electric Enameling Furnace, Showing Charging Fork.

ideal, even for large quantities of pieces, when they are of such size or shape as to be difficult to handle by purely continuous methods. With the use of mechanical equipment to facilitate

easy and rapid handling outside of the furnace, this semi-continuous method is frequently better in economy and satisfaction than automatic continuous methods. An example is the continuous production of parts which are hot-formed in a press from small blocks of steel.

In general, it may be said that the batch furnaces are used largely for heating material the production of which is too intermittent or too small in quantity to warrant the use of a continuous device. Continuous furnaces are higher in initial and upkeep cost, and require steady operation to be economical. The above description of batch furnaces applies as well to the heating of material in liquid baths as it does to open-type furnaces. Material is not heated for forming in liquid-bath furnaces, but the continuous operation is used for treating parts of which only a portion is to be hardened, or when individual careful quenching is required immediately after heating. The heating of wire or strip, fed from reels through a liquid bath, is the most common example of the few purely continuous heat treatments of material in liquid baths.

The size of batch-type furnaces is usually small because of small production, and because the furnace depth to which material can be charged and withdrawn easily is limited. The method of applying heat depends upon the temperature required and the size of the furnace, as covered in the preceding chapter. The overfired method of heating is the only method of heat application not frequently used. It is not necessary to employ this method because there is seldom any mechanism present to make the use of other forms of heat application awkward or difficult. For low temperatures, the underfired form is the most common and usually the best, while for medium temperatures, up to 1900 deg. Fahr. the sidefired design is the best and should be used more often than it is. Batch furnaces are almost always direct-fired above 1900 deg. Fahr., as is true of all forms of furnaces. Remembering that the batch type of furnace is the best for small and intermittent production, with occasional applications to special cases of steady production, we come now to the various continuous arrangements and their peculiar advantages.

Pusher Type.—This method of continuous material handling is probably the most common because it is the simplest, and therefore has the widest range of temperature application. In construction, it is similar to the batch-type furnace, with the additional complication of rails or guides on which the material slides, the construction of which will be considered in another chapter. Of the various constructions for the application of heat, the underfired is the least satisfactory because it is difficult to tie the skids solidly into the hearth. For temperatures below 1600 deg. Fahr. and for small production, rails can be adapted to standard portable underfired furnaces to make an inexpensive equipment, but the underfired construction cannot

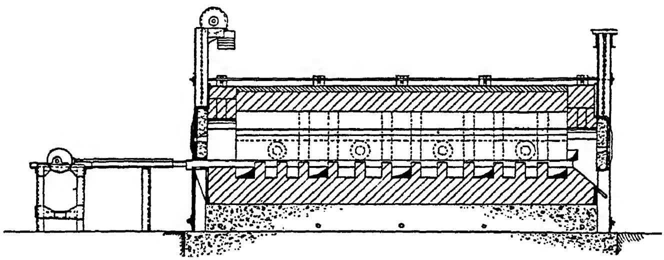


FIG. 29.—Pusher-type Furnace for Heating Small Bars.

otherwise be applied very satisfactorily, because of constructional difficulties. The overfired design is good where the furnace is not too wide and where the temperature does not exceed 1800 deg. Fahr. The sidefired is generally the best construction for temperatures below 1900 deg., and above that temperature the direct-fired arrangement is almost exclusively used.

The general method of operation is either to push the pieces through the furnace directly, where their size and shape allow it, or to push them in pans or carriers. The first method is best wherever possible, and is very simple and satisfactory in most cases, while the second is exceedingly inefficient and troublesome, and will be used only until a better method of handling is devised in each case where it is now used. Figure 29 is a sectional view of a furnace for heating bars $\frac{3}{4} \times 1\frac{1}{4} \times 11$ in. long, these bars

pushing each other continuously through the furnace. The pusher is a cam with a stroke equal to the thickness of two bars, or $1\frac{1}{2}$ in., so that two bars are discharged from each row with each revolution of the common cam shaft.

The variation in method of pushing material through pusher-type furnaces, and in the shape and construction of rails and guides, is great. For large furnaces heating slabs or billets to high temperatures, hydraulic cylinders or mechanical pushers are used, the latter being operated by an electric motor acting

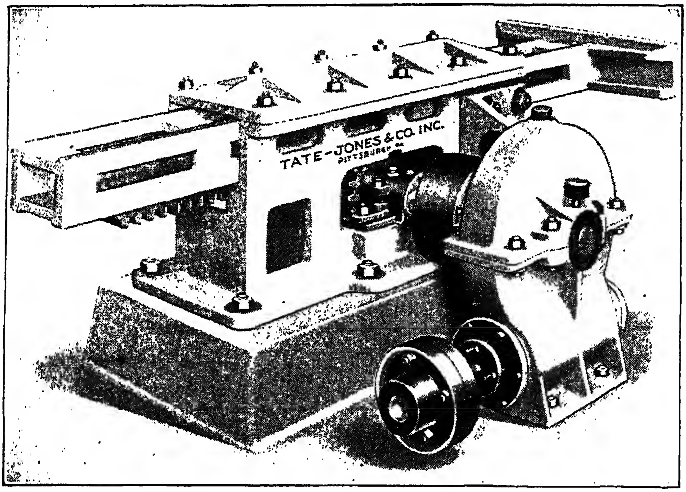


FIG. 30.—A Rack and Pinion Pusher.

through gears, levers, cranks, or screws. Figure 30 shows a mechanical pusher in which an electric motor acts through a suitable gear reduction to drive a heavy pinion, which drives a corresponding rack on the pusher head. This type of pusher has been widely applied to the pushing of sheet bars through sheet and pair heating furnaces. Figure 31 illustrates a lever-type pusher for pushing railroad splice bars, which are prevented from buckling in the furnace by water-cooled hold-down pipes, also shown in the illustration. The motor drive is in a pit below floor level. For smaller furnaces, air pushers, as shown in Fig. 32, are common where the stroke required is over 12 in.

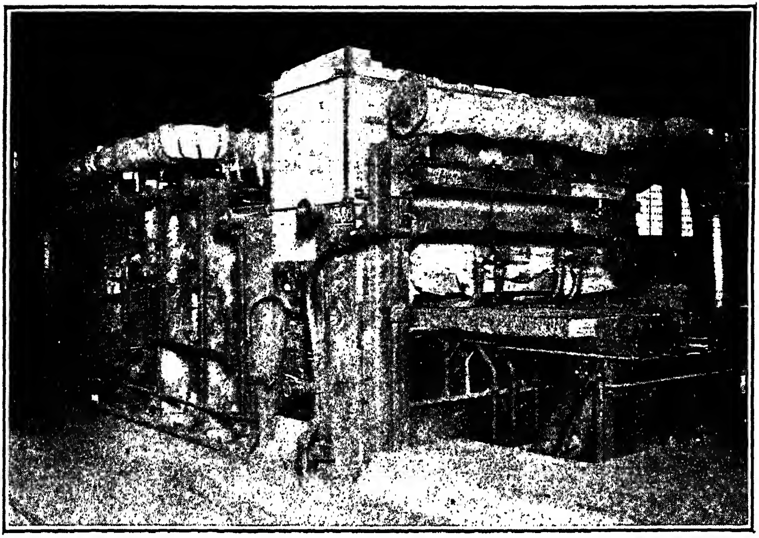


Fig. 31.—A Lever Pusher—Note the Hold-down Pipes.

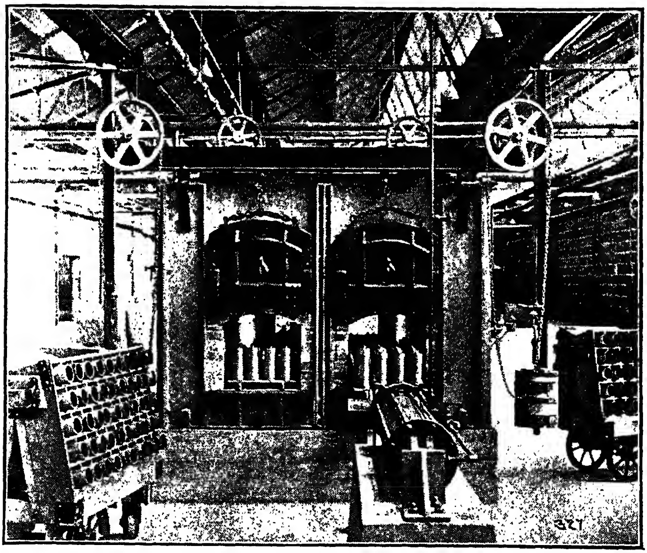


Fig. 32.—Air Cylinder Pusher.

kinds of mechanical variations are employed, depending upon the force, speed, and stroke desired. A slow and powerful force is exerted by a screw, while a push with a wide variation in speed and force can be obtained by using a rack and pinion or a chain-driven ram. For small strokes, a bell-crank arrangement can be designed for any push required, such as the pusher on the furnace shown in Fig. 33. In this type the motor-driven gear reduction drives a crank, which transmits power through a connecting rod to an oscillating shaft. Four reciprocating bell cranks are mounted on this shaft, one for each water-cooled rail upon which material slides in the furnace. The pusher bars of the cranks project through the rear furnace wall on the forward stroke and return to a protected position inside the wall on the return stroke. The movement of the pusher may be automatically controlled by electrical contacts. Figure 34 shows a series of cam-driven levers for pushing a number of rows of material where the force required is small. Further consideration is given to the design of pusher members in Chapter VII.

Pusher-type furnaces are built for all temperatures and in all sizes, and will most satisfactorily take care of large and medium-sized pieces of regular shape with good pushing surfaces, such as bars and billets of all sizes. Thin bars can be pushed on edge if sufficient time is allowed for heating in the furnace thoroughly to heat a solid mass of thickness equal to the width of the bars. Some idea of the effect of size and other factors on the pushing characteristics of shapes can be gained from the following analysis for bars of circular cross-section:

Assume that 4-in. diameter bars are to push each other over horizontal skid rails, which have a maximum variation from level at any point such that the vertical difference between centers of any two adjacent bars will not exceed $\frac{1}{2}$ in. Also assume that the maximum push required to move the bars will equal the dead weight of the bars pushed. (This is common practice in designing pushers for high-temperature furnaces.) With these assumptions, the problem is to determine how many bars can be pushed without buckling.

Figure 35 shows the worst conditions, and observation indi-

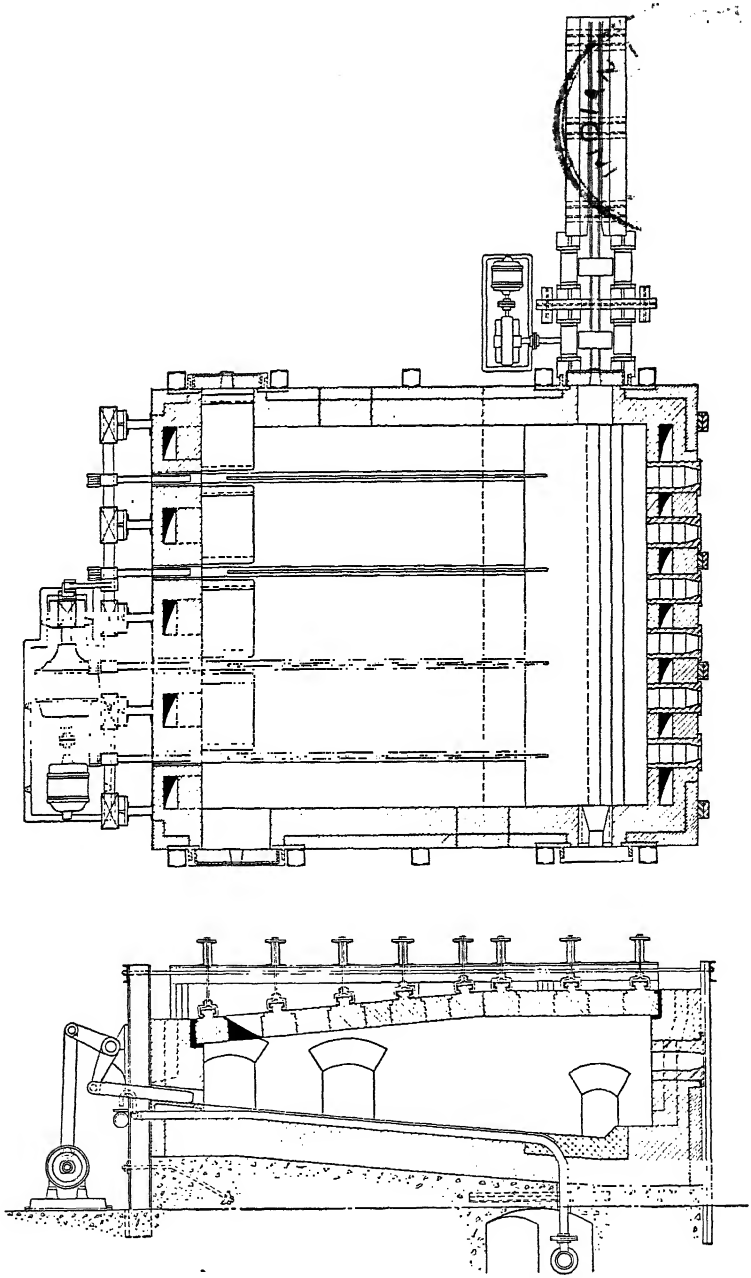


FIG. 33.—Bell Crank Pusher.

cates that under such conditions bars B and C tend to rise by rolling about points O' and O'', respectively, with no initial sliding at point O. For the conditions illustrated,

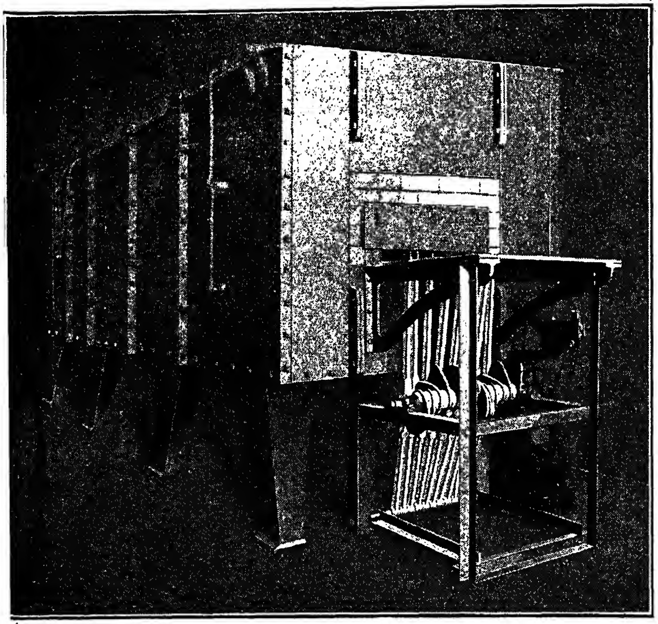


FIG. 34.—An Electric Furnace with Multiple Cam and Lever Pusher.

v = Maximum vertical distance between adjacent bar centers;

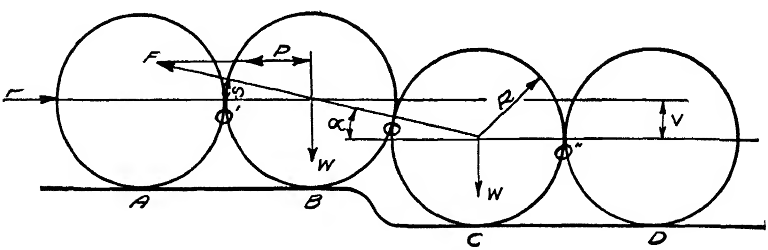


FIG. 35.—Diagram of Forces for Pushing Round Bars.

R = The common radius of the bars;
P = The horizontal push exerted on the last bar;

N = The number of bars beyond point O in the direction of push;
W = The weight of each bar;
F = The resultant force on bar B in direction perpendicular to tangent at point O;
s = The moment arm of force F about point O';
α = Angle between the direction of force F and the horizontal.

Then:

$$\alpha = \sin^{-1}\frac{v}{2R} \text{ and } P = NW,$$

from the original assumptions.

Also, the force F is equally divided between the effort to lift bars B and C (since common frictional force between bars at point O has same moment about points O' and O''), so that the force constituting a moment about point O' will be $F/2$, which is equal to:

$$\frac{P}{2\cos\alpha} \quad \frac{NW}{2\cos\alpha}.$$

The moment arm,

$$s = R\sin\alpha, \text{ so that}$$

$$\text{Moment} = \frac{NWR\sin\alpha}{2\cos\alpha} = \frac{NWR\tan\alpha}{2}.$$

For the critical condition at which bars B and C just commence to rise:

$$\text{Moment } \frac{NWR\tan\alpha}{2} = \text{Moment } WR \text{ acting in the opposite direction.}$$

For this condition:

$$\frac{2}{\tan\alpha}.$$

For the foregoing numerical data:

$$\alpha = \sin^{-1} \frac{\frac{1}{2}}{4} = 7.2 \text{ deg.},$$

$$\text{and } N = \frac{\quad}{\tan 7.2 \text{ deg.}} = 16 \text{ bars beyond point } O.$$

This means that there will be no difficulty, theoretically, in pushing 16 bars of 4-in. diameter on the skid rails of a furnace if none of these bars is more than ½ in. above its neighbor, and if the coefficient of sliding friction between the bars and the skid rails is 1.0. In actual practice, the number will vary on account of complications caused by crooked bars and because the coefficient of friction will be different in every case. The value of 1.0 is not much too high for all temperatures above 1800 deg. Fahr. when the stroke is short and when sticking and inertia must be overcome at the beginning of the stroke. The coefficient is less for temperatures below that point. The minimum is about 0.3 for sliding contact between metal surfaces at low velocity when the metals are entirely cold.

The principal value of a calculation such as the above is in the determination of values with variation of any one factor, all others remaining the same. In this case, the calculation has been repeated for different diameters with all other factors remaining the same, and then for variations in height of adjacent bars for otherwise constant conditions. The results have been collected in the curves of Fig. 36, which show the relative number of bars that can be satisfactorily pushed with different diameters and variations from level.

Sloping the furnace rails is not of any great assistance in preventing trouble from buckling and piling of pushed material. It can be shown by calculation that for the same assumptions as given above, except that the rails are sloped at a 5-deg. angle, only a small percentage of one bar more can be pushed, with theoretical safety, than with horizontal rails.

Rotating Hearths.—This method of handling is increasing in popularity for the heating of many irregularly shaped parts.

It is attractive because the same operator can charge and remove the pieces through adjacent doors, and because the moving mechanism is largely removed from the hot zone, which means a low cost of upkeep. The chief difficulty is with the control of temperature, but with the improvements in electric and gas firing, as well as with the advances in mechanical construction of

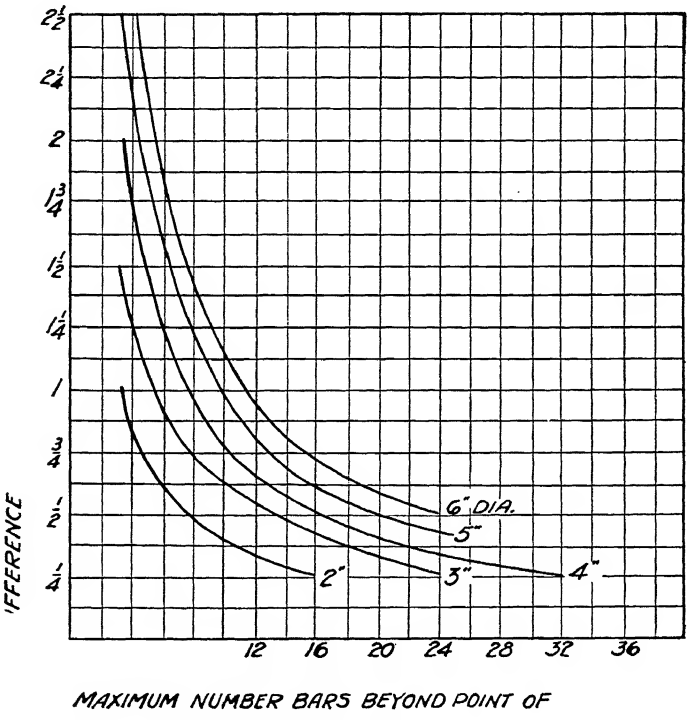


Fig. 36.—Effect of Skid Rail Variation in Pushing Round Bars.

the hearth, these difficulties and objections are gradually being overcome. The operation consists in charging the material on a moving annular hearth, on which it makes one revolution through the hot zone before being removed through the discharge door at the starting point, as shown in Fig. 37. This arrangement will satisfactorily handle pieces that are of such shape as to lie flat and not roll about too much, and would be used much

more frequently for many processes which now employ pans in a pusher-type furnace if its first cost were not so high.

The annular hearth can be rotated on wheels and track or on ball bearings, and is driven through a reduction by means of an electric motor. The sizes built vary from very small units to

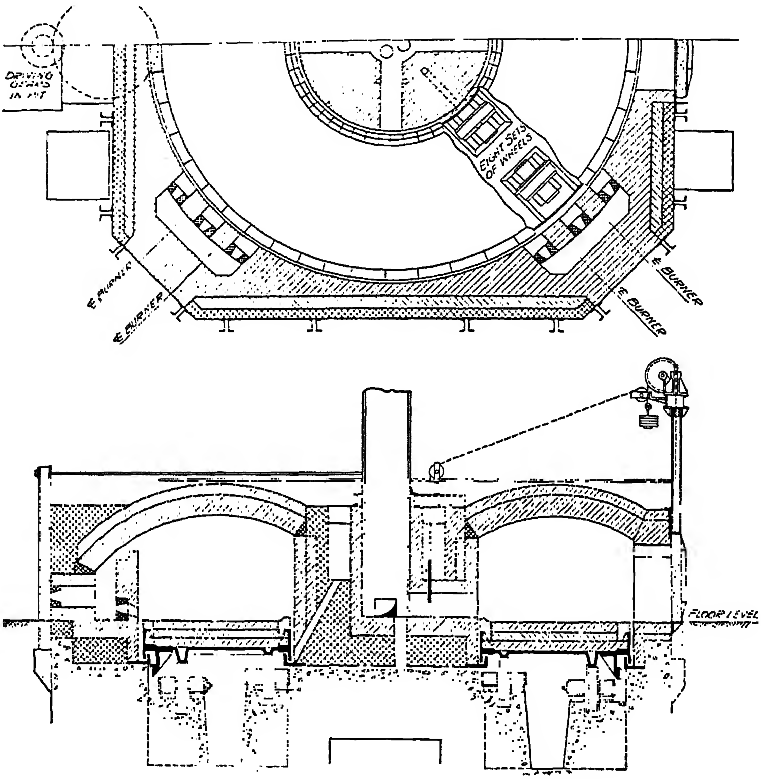


FIG. 37.—A Rotating-hearth Furnace.

hearths having an inside diameter of 12 ft., without greatly affecting the constructional problems involved. Because of the hearth arrangement, it is difficult to use the underfired method of firing, and the construction of the overfired design is made hard by the circular shape, although this latter method is probably the best that can be found. The usual construction at present is to have the burners in fuel-fired furnaces fired tangentially

from the outside in a "dog-house" construction
good as side firing with a proper bridgewall, but
direct firing. Rotating furnaces have been built for
but are not particularly satisfactory. There are reports of successful operations, but the process of forging is frequently confused with that of forming, which requires a lower temperature; and to the author it is a question whether any of them have been operated long enough at temperatures above 1900 deg. to cause the formation of slag, which would be fatal to this construction.

Car Type.—The car-type furnace is the one most commonly found wherever annealing of steel or castings is done in quantity. It is particularly appropriate for the annealing of all sizes of pieces, because annealing is a heating and cooling operation which can be done in batches, and the car-type furnace is nothing more than a large batch-type furnace with a valuable labor-saving feature for the handling of material. It is capable of very accurate temperature control, and can be ruggedly built to stand up for long periods of time without requiring repairs. Since most annealing treatment requires the allowance of a soaking period after the material has been brought up to temperature, it is possible to pile the material rather high on furnace cars and yet be assured that every piece will be thoroughly heated and annealed. Most pieces to be annealed are heavy in section and not subject to serious warping, so that there is no disadvantage in the heavy charging in most cases, as long as the rules for capacity given in the preceding chapter are not violated. Figure 38 shows a typical loaded car. The construction allows scaling to be reduced to a minimum, and the cooling cycle can be quite closely regulated.

The cars are generally constructed with flanged wheels, but sometimes cast-iron balls are used for very heavy loads, as in the case of box annealing of steel sheets where the sheets themselves and the very heavy protecting cast-iron box must be moved. Sand seals are used on all sides to prevent air infiltration into the heating chamber and to protect the running gear from heat. The underfired arrangement is seldom used except in some cases where coal is used as the fuel and the products of combustion

are taken to the heating chamber through ducts under the furnace, or for some low-temperature ovens for drying purposes. Direct firing is unsatisfactory because the operations for which a car-type furnace is used never exceed 1800 deg. Fahr. in temperature, and the sidefired design is much the best and most common arrangement. The overfired design is sometimes used for accurate temperature control, as in the case of the furnace shown in Fig. 32.

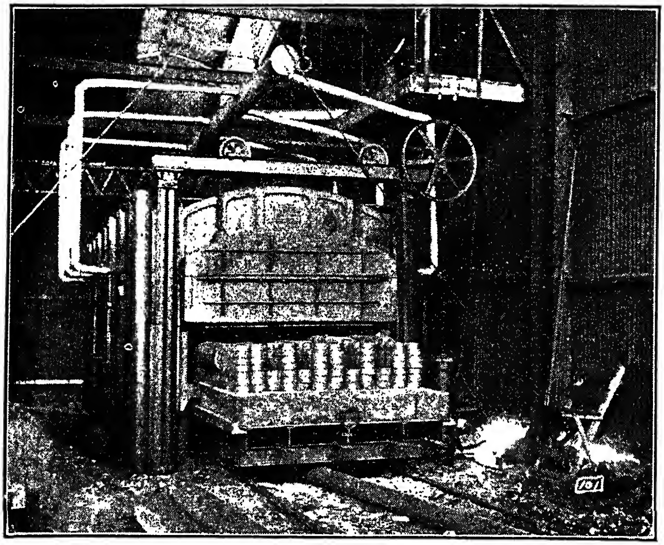


Fig. 38.—An Overfired Car-type Furnace.

Car-type furnaces are used for low temperatures, as in the case of drying and core ovens, and for temperatures up to 1800 deg. maximum. There is practically no limit to the size that can be built, there being car types in operation which are 30 ft. long and 12 ft. wide and high. The electrically heated elevator furnace is a variation of the car-type furnace. In this design, the furnace is elevated, and the car lifted by means of an elevator up to the bottom of the furnace, where it seals the only opening in the heating chamber. The remainder of the furnace she welded tight so that flow of air into the heating chamber i

tically eliminated and an ideal atmosphere is obtained for the annealing of electric motor armature laminations and other very

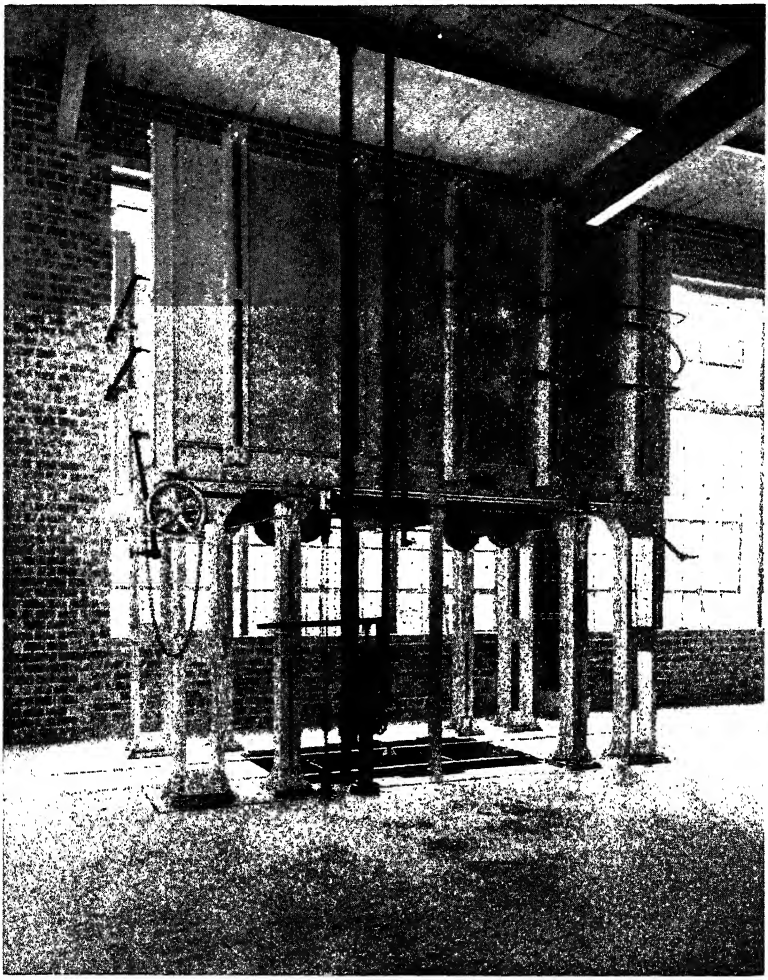


FIG. 39.—An Electric Elevated-car-type Furnace.

accurate work in large quantities. Figure 39 is a view of one of these furnaces.

ain Conveyor.—This type is ideal for many operations, difficulty lies in the fact that the advantage is too fre-

quently theoretical, and practice results in endless trouble. The usual chain conveyor is designed to carry the work through the furnace and discharge it through a chute in the discharge end, and in some cases this can be very well accomplished if the mechanism is made sufficiently heavy, but too many attempts are made which have no chance of success because the effect of temperature on metallic alloys is not fully realized.

There are a number of variations of the chain conveyor, including flight conveyors (chains carrying plates to form a solid hearth); chains that actually carry the heating material which is laid across them; and chains having fingers, or attachments, which carry the material through the furnace. The first style is the most difficult to construct (as well as the most needed by industry) because of warping of materials under heat. Although small furnaces of this sort have been built and kept in operation for one year with few repairs at 1800 deg. Fahr. by using the best alloys and very careful construction, they are exceptional, and their desirability was probably reduced by their great initial cost. The second type, which is useful for such material as automobile axles and other pieces of tapering diameter, can be quite satisfactorily designed. The third arrangement has the best chances for success, because the chain itself can be protected by brickwork, the fingers being allowed to project through suitable slots. But any chain conveyor, to be a success, must be reliable, because otherwise the increased fuel consumption in heating the chain, added to the cost of upkeep, will more than overbalance the labor saving. The chief mechanical difficulty with chain conveyors is the fact that the linear expansion of a chain of the usual furnace length, when heated, is a considerable proportion of the pitch of the chain (distance, center to center of adjacent openings for sprocket teeth). The chain is then out of pitch with the sprockets and tends to climb, with the result that the chain rides off the sprockets or skips a sprocket tooth with a sudden jerk. These sudden shocks put a tremendous strain on the chain and further stretch it until eventually a break occurs. Only by special ingenuity can this action be avoided. The underfired arrangement of heat application should not be

used in a chain conveyor furnace, because it further complicates an already complicated design, and just as good results can be obtained with an overfired construction or by sidefiring. No chain conveyor will stand up where direct firing is satisfactory, so that the two are never found together, except where the chain is protected by brickwork.

Roller-hearth Type.—The furnaces coming under this heading are in the same class as the chain conveyor, in that their temperature range for satisfactory operation is very definitely limited, because almost all of them employ moving metal parts exposed directly to the heat of the furnace. They must consequently be designed with a great deal of thought, and given careful consideration with regard to all conditions to be met, before they are selected.

The roller-hearth type is of two common forms: one used for the continuous annealing of sheets which are carried through the furnace on revolving alloy discs; and the other for hardening, annealing, or drawing flat pieces, or small pieces in pans, which are carried through the furnace on closely spaced rollers. The first type is well standardized in sheet mills and works very satisfactorily when properly designed so that the sheets are not scratched. The discs are mounted on water-cooled shafts protected from the furnace heat to some extent by brickwork and driven by chains and sprockets outside the furnace, which is fired by oil or gas. The second type has been successfully installed in several instances, and these furnaces give excellent results if the rollers are not made smaller than 1 in. in diameter on about 2-in. centers. This limits this design to pieces that are large enough to be satisfactorily carried on this arrangement of rollers unless uneconomical pans are used, but there is a wide field in the bigger parts, particularly various kinds of gears. The rollers are of alloy and driven by sprocket and chain or by bevel gears outside the furnace, this mechanism being protected from dirt and the entire set of interconnected rollers driven by motor and gear reduction as shown in Fig. 40. Most of the furnaces of this type built to date have been electrically heated, but gas can be applied successfully. The temperature limit is about

1700 deg. Fahr. for satisfactory life of the parts. The roller-hearth furnaces of the latter type are limited in width to about

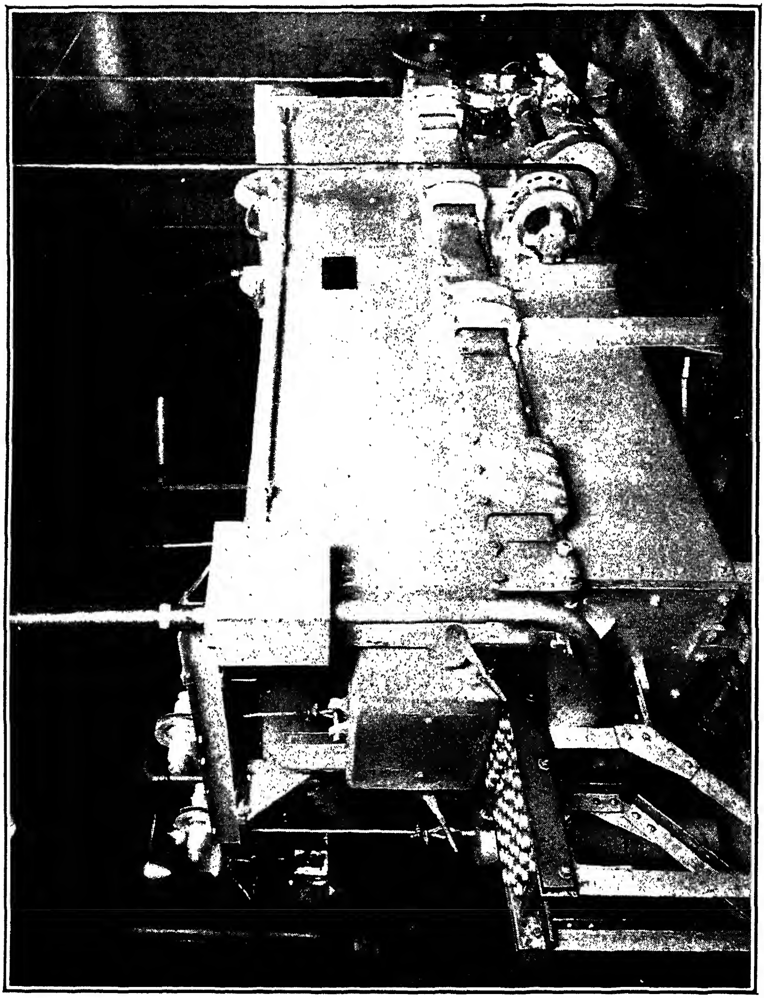


FIG. 40.—A Roller-hearth-type Furnace.

2 ft., by the strength of the rollers when hot, but this is wide enough for most requirements.

Moving-hearth Type.—This includes various devices designed to move material through a furnace by means of a which itself remains inside the furnace at all times.

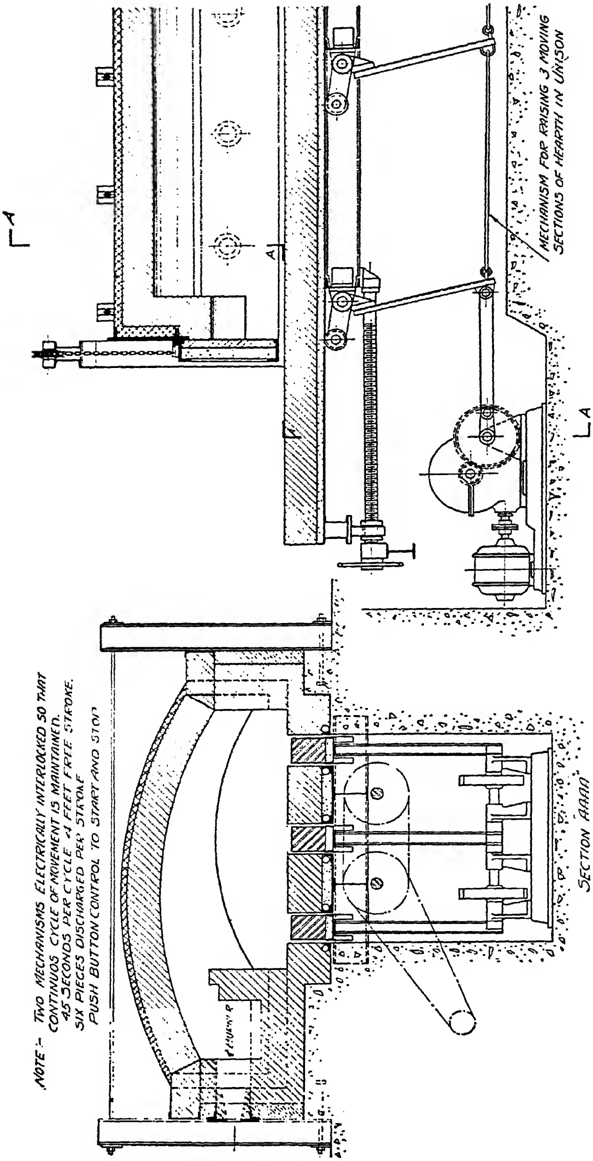


FIG. 41.—A Form of the Walking-beam Type of Moving Furnace Hearth.

is the walking-beam design illustrated in Fig. 41. In this furnace, longitudinal sections of the hearth pick up the heating material from rests on the hearth, move it forward, set it again upon the rests, and move back at hearth level to the original position before again rising to pick up the material. The vertical movement is accomplished by cranks and levers which raise and lower the rollers upon which the hearth sections rest. The horizontal movement may be accomplished through a motor-driven screw or an air cylinder. The vertical and horizontal movements may be interconnected so that they act simultaneously, but with the carriers moving forward at the same time that they are rising there is danger of scratching the material. The best arrangement is to have the movements follow each other separately and in order, so that they describe a perfect rectangle. These independent movements may be connected by electrical contacts so that they will follow each other continuously in the proper sequence and at the proper time. Another type of moving hearth embodies reciprocating lugs which engage the heating material, drag it forward on the forward stroke, and turn down out of the way on the return stroke.

Rotary Muffle Type.—In this type of furnace, which is shown in Fig. 42, small pieces are carried through a spiral retort of alloy, which is externally heated. For many pieces, this method eliminates pans, and produces a very even and satisfactory heat treatment for annealing, hardening, or drawing. The muffle is revolved on rollers outside the heating chamber, and is driven by an electric motor through suitable speed reducers. These furnaces are fired by gas, which is burned in the brick-lined chamber surrounding the muffle. The small rotary-muffle furnaces are usually gas-fired, while the larger types, mostly used for heating cement, chemicals, and other materials in bulk form, are fired by coal, oil, or gas. In all cases over 1200 deg. Fahr., direct firing is employed, and works very satisfactorily, because the drum acts as a baffle to sustain ignition, and because the revolving of the drum, together with its high thermal conductivity, equalizes the temperature in the furnace and prevents localization of the heat at the burners.

A variation of this furnace is the rotary-muffle furnace used for the gas process of carbonizing, as distinct from the common method of packing parts in boxes with solid carbonizing material and heating these boxes in batch-type or pusher-type furnaces. In the gas process, small parts, such as stampings, are rotated in the heated muffle into which gas, which has a carbonizing action, is introduced, so that each piece receives a thorough

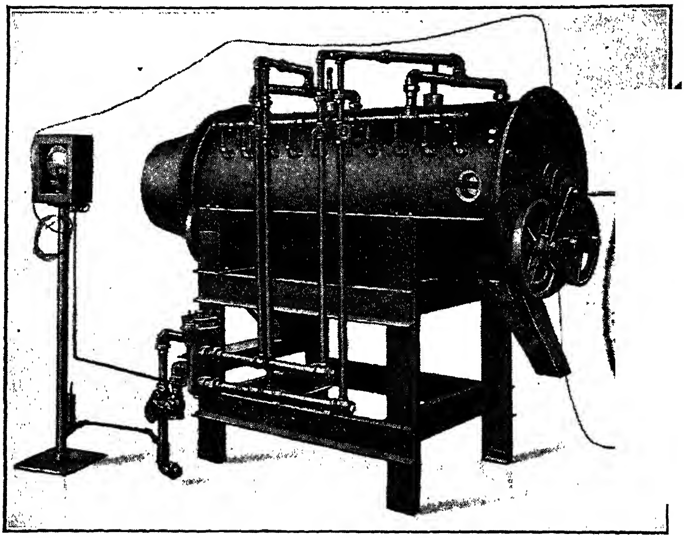


FIG. 42.—A Rotary Muffle-type Furnace.

carbonizing treatment. The furnace is arranged so that it can be tilted to discharge the pieces after treatment.

This completes the detailed consideration of the different methods of material handling inside the furnace. Having studied the classification of heating arrangements according to temperature in the last chapter, let us now again divide the various processes into temperature classes and summarize the common material handling designs available, as an assistance in selecting a suitable furnace to meet a set of specific conditions.

Applications of Heating Arrangements and Material Handling

In the preceding chapter, the various industrial heating processes were divided into a number of groups according to temperature, and the best methods of heat application outlined for each of these temperature groups. To follow this same procedure in studying the methods of material handling, the number of groups can be conveniently made smaller and are best divided as follows: Group A, temperatures from 400 to 1000 deg. Fahr.; Group B, temperatures from 1000 to 1900 deg.; Group C, temperatures from 1900 to 2500 deg.

Group A: 400 to 1000 deg. Fahr.—This includes drawing and normalizing processes, and is selected because it includes the temperature limits in which malleable-iron, cast-iron, and steel parts can be used to produce an infinite number of successful mechanical continuous arrangements. Temperatures in this range are not great enough to produce color in the furnace, and although it is the hardest range in which to attain even temperature distribution, the temperatures are not great enough to promote any considerable scaling or greatly to weaken metallic members, so that such members can be made quite complicated and yet have a very satisfactory useful life. Scaling is simply the increased affinity of metal for the oxygen of the air. This affinity increases with temperature but does not become seriously active until temperatures above 1000 deg. are reached. Except for some drying operations, car-type furnaces are seldom used, because pieces, to be satisfactorily drawn, can seldom be piled, and the rotary furnace is infrequent because of the cost. The best arrangements are batch type for small production, chain conveyors and moving hearths for large production, and pusher type with pans for small pieces that cannot be handled on any form of chain conveyor.

Group B: 1000 to 1900 deg. Fahr.—This includes annealing, hardening, carbonizing, forming, and pressing operations, and offers greater difficulties to mechanical design. The greatest number of failures lie in the upper half of this range, because

any mechanical features at these temperatures require extreme care in design and construction, and experience with the behavior of structural materials under heat. Steel parts are out of the question, because of oxidation. Cast iron and cast steel are better, and frequently satisfactory up to 1500 deg. in temperature, but above this point they can be used only for very heavy parts, such as wearing plates, which are not subject to tensile strain. Alloys are excellent up to 1600 deg. for most purposes, but above that temperature care must be taken to make them sufficiently heavy to counteract their plasticity and loss of strength and rigidity.

Rotating-hearth, pusher-type, and car-type furnaces can be readily built for these temperatures, and are found in large numbers for all kinds of heating operations. Many chain conveyors and roller and moving hearths are operating successfully, but most of these are successful only after sad and expensive experience. The refractory construction of furnaces for these temperatures offers little difficulty, as first-grade firebrick will show little effect when the furnace is correctly designed. The chief sources of trouble are in the hearths of underfired furnaces and in the arches of overfired furnaces, where the brick is exposed to heat on all sides.

Group C: 1900 to 2500 deg. Fahr.—This range can boast of few successful continuous arrangements except for large pieces, because no metal at present available will last long at these temperatures, and even refractories are soon destroyed. Water cooling must be used in most cases where metal is exposed to the heat of the furnace, and this increases the complications and difficulties in the road of any very successful accomplishment. Steps are being taken in the way of extensive experimenting, and results may be looked for in spite of difficulties to be overcome.

The only two methods of material handling in common and successful use in this range are the batch operation as used for most forging and some rolling operations, and the continuous pusher type commonly used for heating billets and slabs in preparation for rolling into rails, tubes, sheets, and structural shapes. The soaking pit used for heating ingots for the blooming

mill is a variation of the batch-type furnace and is not unique except for its underground construction to facilitate handling by an overhead crane.

Having looked at these various groups in some detail, we can conclude these considerations by showing the methods for both heating and material handling for the different groups in tabulated form, before studying the procedure to be followed in selecting the right arrangement for any special case. This table will appear as follows:

Process	Method of Material Handling	Method of Heat Application
Group A:		
Drying....	Car type...........	Underfired.
Drawing...	Batch.............	Underfired, overfired, or closed sidefired.
	Chain or moving hearth	Underfired, overfired, or closed sidefired.
	Pusher type..........	Overfired or closed sidefired.
Group B:		
Annealing or hardening..	Batch...............	Sidefired or underfired.
	Car type.............	Sidefired or overfired.
	Pusher type..........	Sidefired or overfired.
	Chain or moving hearth	Sidefired or overfired.
	Rotating hearth......	Sidefired.
	Rotary muffle........	Indirect-fired.
Carbonizing..	Rotary muffle........	Indirect-fired.
	Car type.............	Sidefired or overfired.
	Pusher type..........	Sidefired.
Forming.....	Batch...............	Sidefired.
	Pusher type..........	Sidefired.
Group C:		
Forging and rolling.....	Batch...............	Direct-fired.
	Pusher type..........	Direct-fired.

This is all very general, and, although it is necessary knowledge for the intelligent consideration of the problem of selecting

the right furnace, it does not definitely tell how to answer the question: "How can the best method of handling material be determined for certain given conditions?" Let us see how this problem can best be analyzed.

SELECTION OF METHOD OF HANDLING MATERIAL

To begin with, it must be realized that this question is entirely too broad for a general solution that will satisfy any conditions that it is necessary to meet. The best that can be done is arbitrarily to limit the conditions and show how, for these limited conditions, the question can be answered. The same method can then be used for other conditions with the data revised to suit. The following assumptions are made in this case:

1. All furnaces compared assumed to be oil-fired.
2. Production in all cases assumed to be steady, not intermittent.
3. The same amount and sizes of pieces heated per hour in each furnace of those compared.
4. Same heat treatment assumed in each comparison.
5. Open-type furnaces considered in all cases. No pots or muffles considered.

For these conditions, the various kinds of furnaces in the three temperature groups can be compared as examples of the method, by consideration of the four principal factors which determine the best method of material handling. These factors are:

1. Fuel consumption.
2. Cost of furnace upkeep.
3. Depreciation charges on furnace investment.
4. Labor saving.

The object of the comparison is, of course, to determine whether a certain continuous arrangement, as compared with batch operation or to some other continuous method, will save sufficient labor to pay for its installation and for any disadvan-

tages which it may have in fuel efficiency or upkeep cost. This is solved by determining the comparative total cost of the factors —fuel, upkeep, and depreciation—over a period of time such as one month.

The data for this determination cannot be entirely accurate for a comparison as general as this particular example, but good average figures will be used in order to show the method of comparison. For the first item, fuel consumption, it is assumed that all the furnaces in group A are based on a production of 1000 lb. of material per hour; Group B, 2000 lb. per hour; and Group C, 4000 lb. per hour. On a basis of 250 working hours per month and 7 cents cost of oil per gallon delivered to the burners, the relative monthly fuel costs were figured with the following average oil consumptions per ton of steel heated:

	Gallons per Ton
Group A:	
Batch	15
Chain conveyor	18
Group B:	
Batch	20
Rotating hearth	18
Pusher-direct	20
Pusher-pans	30
Alloy chain	24
Group C:	
Batch	30
Pusher	26

Question of upkeep involves life of refractories and metal parts, and power for mechanical drives. The monthly cost in this case was determined by finding the size of furnace required in each case, assuming the best grade of material, and figuring the replacement material on the basis of the following average life:

TABLE 10

AVERAGE LIFE OF FURNACE PARTS

Refractories

Group A:

No replacement.

Group B:

Underfired hearths	6 months.
Bridgewalls	12 months.
Sloping floors	12 months.
Level floors	36 months.
Arches	18 months.
Muffles	20 per cent yearly replacement.

Group C:

Arches	6 months.
Door jambs	3 months.
Bridgewalls	3 months.

Weekly patching of door jambs and hearths.

Metal Parts

Deg. Fahr.	Cast Iron	Alloy
400–1600	*	
1700	1 year (min.)	3 years.
1800	5 months.	2 years.
1900	1 month.	18 months.
2000	Not used.	6 months.

* Will last as long as useful life of the furnace.

The monthly charges for depreciation, given in the final table of costs below, were determined in each case by estimating the cost of the furnace required and assuming the same life for all of the furnaces in each group. Depreciation, interest, and taxes were then calculated in accordance with usual accounting practice.

The following table gives the comparative costs, worked up from the above methods of calculation:

COST PER MONTH, DOLLARS

Type	Fuel	Upkeep	Depreciation	Total
Group A:				
Batch	131	12	10	153
Chain conveyor	157	22	29	208
Group B:				
Batch	350	8	16	374
Rotating hearth	315	10	115	440
Pusher-direct	350	40	32	422
Pusher-pans	525	49	33	607
Chain conveyor	420	30	84	534
Group C:				
Batch	1050	125	38	1213
Pusher	910	165	88	1163

The difference between the totals for any two types in each group represents the amount which must be saved in labor to make the more expensive furnace pay. It is surprising to note the great importance of fuel economy in this consideration, and it appears that it is profitable, at least for the conditions which we have assumed in this case, to spend considerable money for upkeep and initial cost if a reduction can be effected in fuel consumption. It is also noticeable that the increase in maintenance of many continuous arrangements, compared with that of batch-type furnaces, is small, so that the saving of one man's time at ordinary labor costs will more than pay for the increased investment, without considering other advantages resulting from continuous operation. It must be remembered, however, that all the foregoing figures are based on proper design, one particular production, and fuel oil, and that these comparisons may be entirely different for other conditions. Each case is an individual problem, but the solution follows the same general method as given. Many cases could be presented to show bad practice, where the labor required to keep the equipment operating is greater than the handling labor saved, but in general it may be said that furnaces can be made successfully continuous if

complicated arrangements are avoided by strict adherence to tested data on life of materials of construction under different heat conditions.

In selecting the general form of heating furnace it remains now to review the method of consideration of the three chief factors which have been discussed in detail: heat application, capacity, and material handling.

Review of Factors in Selection of Furnace Type

The process of thought best adapted to the proper selection of the right furnace type for a given set of conditions can be satisfactorily divided into the following steps:

1. Determination of capacity and size required.
2. Elimination of those methods of heating and material handling which would be entirely unsatisfactory to the conditions.
3. Determination of most efficient method of handling material from available methods remaining.
4. Determination of method of heating best suited to size and mechanical arrangement selected.

The first step has already been discussed in detail in the preceding chapter. The second step requires a study of the various methods available, such as is given in a general way in this chapter and the preceding one, but with particular attention to the definite conditions to be met. The third step involves the method detailed in the preceding paragraphs, again with respect to specific conditions. It is assumed that the fuel has already been selected and that its price is known. The amount of fuel must be roughly estimated. The cost of upkeep of the various types to be considered must be determined, with the local cost of material and labor. Prices on the various designs must be obtained and the depreciation charges calculated. The last step is again a general study with conditions in mind such as temperature required, accuracy of regulation necessary, and the furnace size which must be uniformly heated. When all

these steps have been carried through, a rough sketch of the furnace can be prepared, and the next problem is the more accurate determination of fuel consumption, on which the actual design will be based. This will be the subject of the next chapter. But before passing to this phase, let us consider briefly the handling of materials outside the furnace.

Material Handling Outside the Furnace

This question is not strictly a part of furnace design, but it is definitely a subject with which the furnace engineer must deal, and will be considered to the extent of describing some of the common devices in use. The problem of handling material outside a heating furnace can be divided into three separate movements: charging, discharging, and conveying to and from the furnace.

The charging of a furnace depends on the size, weight, and shape of the material and the character of the furnace to be charged. In batch-type furnaces, the material must ordinarily be actually inserted into the furnace and deposited on the hearth. This is accomplished by a number of methods designed to save labor, including the jib crane or overhead hoist and chain, as shown in Fig. 27 for forging ingots; the monorail and suspended tongs or peal for medium billets, slabs, and forging bars; and the electrically driven unit charging machines or trucks, as shown in Figs. 43 and 44, used for large pieces and carbonizing boxes. For continuous furnaces, the material is usually charged on to the conveyor which carries it into the furnace, or, with pusher-type furnaces, on to the charging table between the pusher head and the furnace, as shown in Fig. 31. This is usually accomplished by a simple chain, air, or electric joist, which picks up the pieces from a convenient pile near the furnace. Small pieces are frequently automatically charged into continuous furnaces from a hopper, as in Fig. 45, or slid down a chute on to the continuous hearth. In pusher-type furnaces charged from the side, the pieces are either carried into the furnace on power-driven rollers located inside the furnace or

Fig. 43.—A Billet-charging Machine.

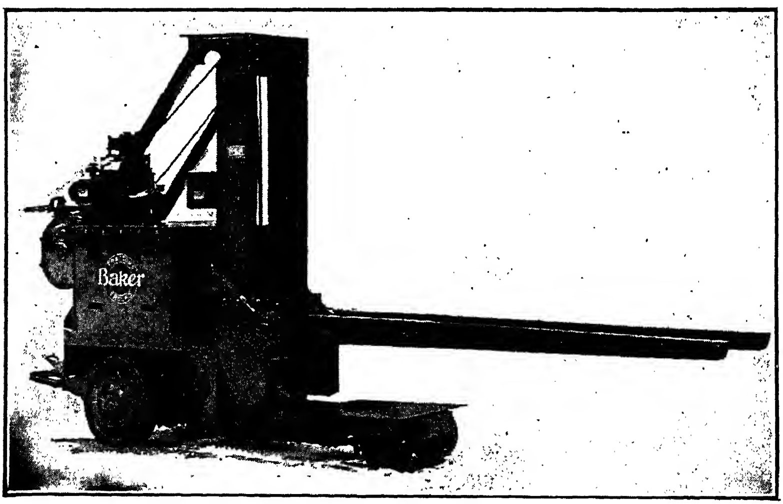


Fig. 44.—An Electric Lift Truck, Useful in Charging Furnaces.

pushed in by a mechanical pusher, such as the chain-driven pusher of Fig. 46.

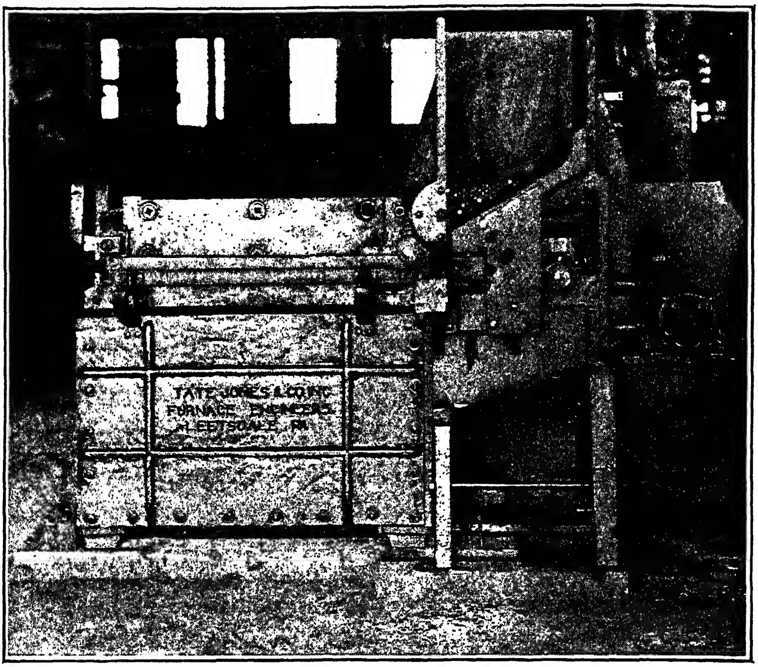


FIG. 45.—A Patented End-heating Furnace, Showing Charging Hopper.

Discharging a furnace, in the case of batch operation, is usually done in the same manner as charging. In many cases of

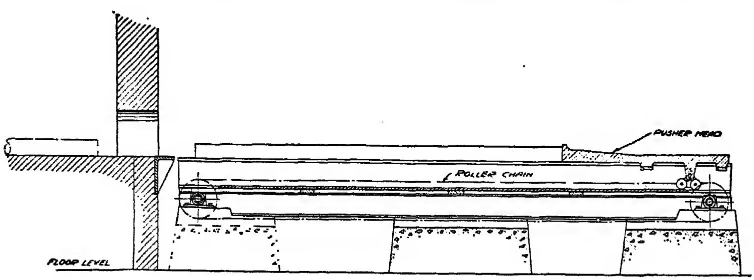


FIG. 46.—A Chain-driver Discharging Pusher.

continuous furnaces, discharging is done by gravity by const ing a chute at the discharge end of the furnace. This

is usually necessary in the case of hardening furnaces where the material must be discharged quickly into the quenching tank. In large continuous furnaces the pieces are either discharged by gravity or carried out of the furnace by a mechanical pusher or conveyor.

Transverse chains, passing through the furnace and returning in water under the furnace, as indicated in Fig. 21, have been

Fig. 47.—A Machine for Turning Ingots in a Continuous Furnace.

successfully used for discharging billets from the side of continuous furnaces, but pushers are more commonly used. The common type comprises a pusher bar gripped by power-driven rollers or gears, which carry it in and out of the furnace, as shown in Fig. 33. The end of this pusher bar, which may be a gular steel bar or a water-cooled pipe with flexible water tions to allow movement, strikes the end of the piece to

be discharged and pushes it out through a door on the opposite side of the furnace. Figure 47 shows a machine for turning large ingots on the discharge hearth of a large continuous pusher-type furnace. The machine enters the furnace through the side doors and manipulates the heavy ingots as desired.

Handling material to and from a furnace again depends on the nature of the pieces or containers and of the operation. In many processes, roller or belt conveyors are used to transport the material to the furnace and from the furnace to its next

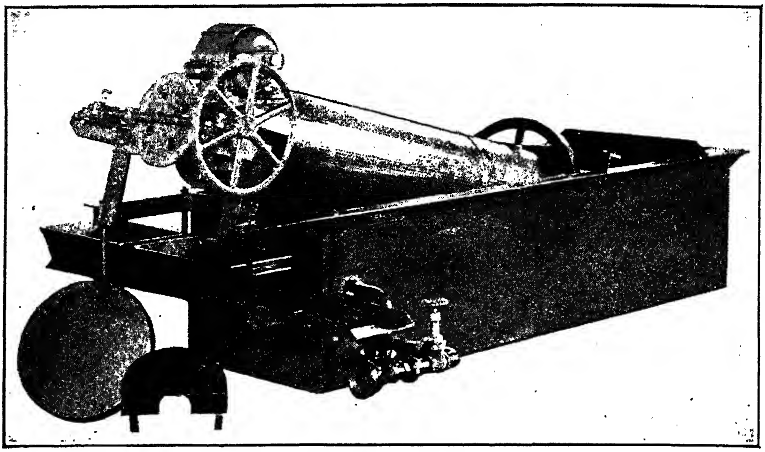


FIG. 48.—An Automatic Quenching Tank with Rotating Perforated Drum.

operation. Heavy roller conveyors or monorail tongs are usually used in steel mills to take the pieces to the rolling mills from the furnace. For quenching operations, an interesting development is the automatic quenching tanks, such as those shown in Figs. 48 and 49. With these units, the material is discharged into the tank from the furnace chute and slowly carried out of the quenching liquid by a conveyor, which insures a thorough and uniform quench. This conveyor frequently discharges the pieces directly on to the conveyor of a drawing furnace, so that no handling labor is required from the time that the piece is charged into the hardening furnace until it is discharged into containers at discharge end of the drawing furnace. It does away in

plants with the cumbersome method of baskets in the quench tank which must be taken out when full by means of a chain hoist.

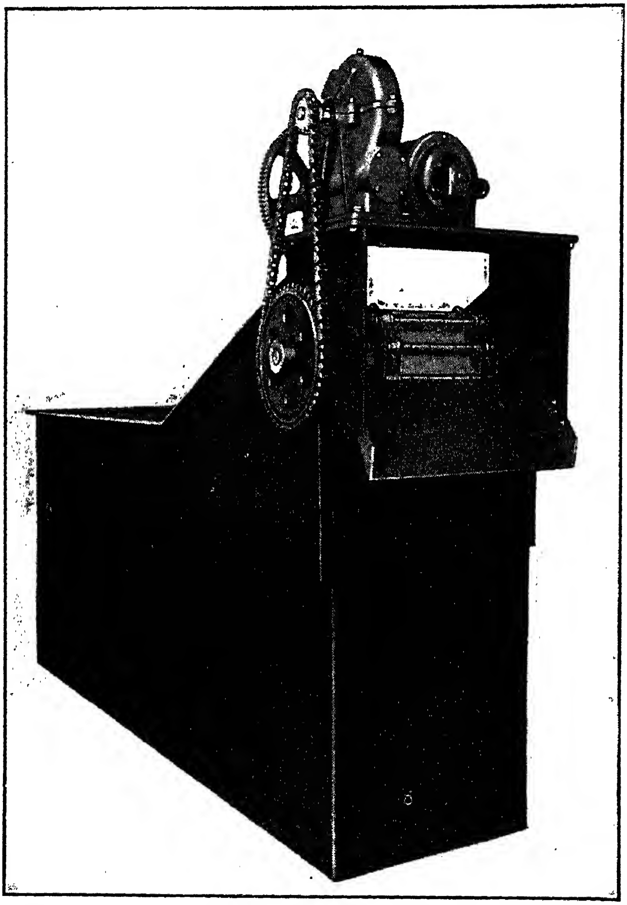


FIG. 49.—An Automatic Quenching Tank with Flight Conveyor.

This completes the general considerations necessary in preparation for the more detailed subjects of actual furnace design to be considered in the following chapters.

CHAPTER V

FUEL CONSUMPTION AND HEAT SAVING

In the preceding chapters of this book, the various initial considerations of an industrial furnace installation have been discussed in the sequence in which they arise to confront the executive or engineer who is selecting or designing such an installation. These initial studies covered the questions of the proper fuel to use, the arrangement of furnace interior for proper application of this fuel, and the handling of material in the furnace. The answers to the first two questions depend to some extent on a knowledge of the approximate amount of fuel which will be burned in the furnace, and the actual design of the furnace will require a still more accurate idea of this amount. It is appropriate, therefore, to introduce at this point a more detailed investigation of the fuel consumption of the various furnaces that have been discussed.

As is the case with most features of industrial furnace design, the nature of the question of fuel consumption is such as to make it extremely difficult to formulate any general rules for its determination. There are so many variable factors involved that even in strictly definite examples it is impossible to predict with absolute accuracy what amount of fuel will be required to accomplish the required heating results. However, the theory involved in the determination of fuel consumption is the same for all kinds of industrial furnaces and can be discussed generally before considering the variables which make the application of this theory to practice difficult.

In the operation of any furnace, regardless of the fuel utilized and the purpose for which the material is heated, the heat involved may be divided into three parts which are (1) total

heat introduced into the furnace, or *heat input*; (2) heat absorbed by the heating material, or *useful heat*; and (3) heat lost in various way, or *heat losses*. The fundamental rule on which the theory is based is that part (1), *heat input, is always exactly equal to the sum of the other two parts, useful heat and heat losses*; but the exact determination of each of these parts is always difficult. Since the value of the heat input can usually be quite accurately measured for furnaces already in operation, a method of estimating the fuel consumption of a new furnace is to find a similar one already in operation and guess at the probable effect of any differences between it and the proposed furnace. If the information obtained is strictly reliable, which for various reasons is frequently not the case, and if there is not a great difference in size and design between the two furnaces, this method is excellent, and in any case it is a valuable check on calculation. In most cases, however, reliable and applicable information is not available, and the fuel consumption must be estimated from a knowledge of both theoretical methods and practical operating figures for different conditions.

In this chapter, we shall first discuss the methods and data applying to the theoretical determination of fuel consumption and power consumption in fuel-fired and electric furnaces. We shall then study the practical values of fuel requirements in different types of furnaces, and the use of these values in checking the theoretical figures. Finally, the various methods of heat saving will be considered.

Theoretical Determination for Fuel-fired Furnaces

The method of procedure to be followed in the theoretical determination of fuel required is to set up a heat balance, similar in form to a financial balance sheet, in which the various divisions of each of the three groups outlined above are represented and totaled, and the totals made to conform to the fundamental rule that heat input equals useful heat plus heat losses. The number of divisions in each group depends on the furnace type, fuel used, heat-saving appliances, etc., and the following list is intended

to cover all of the possibilities (not including heat developed in the oxidizing of heated metal, which can be neglected, or other chemical changes in the heated material):

Group (1) Heat input:

1. Heat contained in fuel burned.
2. Sensible heat in fuel due to preheating.
3. Sensible heat in combustion air due to preheating.
4. Heat in material which has been reheated before charging.

Group (2) Useful heat:

5. Heat absorbed by heating material in the furnace.
6. Heat equivalent of waste-heat boiler power developed.

Group (3) Heat losses:

7. Sensible heat leaving furnace in flue gases.
8. Radiation from walls.
9. Absorption of heat by furnace walls.
10. Heat to conveyors, containers, or cars.
11. Heat to water in water-cooled parts.
12. Heat through doors and openings.
13. Heat in fuel escaping unburned.

It is necessary to examine each of these items in more detail before being able to set them up in the heat balance desired. As stated before, the exact determination of all these items is theoretically difficult, and the simplest practical methods will be used wherever possible.

1. Heat Contained in Fuel Burned.—This quantity is the chemical-energy content of the fuel converted to heat-energy units, because when the fuel is burned by the rapid oxidation process of combustion the energy is practically all liberated in the form of heat and remains in this form throughout the remainder of the heating process. The heat content, expressed in this country in British thermal units (B.t.u.), is either actually measured by a calorimeter or calculated from the chemical analysis, and is always given as a part of the specifications of any

industrial fuel. Chapter II gave the lower heat contents of various solid, liquid, and gaseous fuels commonly used for industrial furnaces.

The heat-content value for fuels is usually designated by the term lower heat content, which means the higher heat content (entire energy content of the fuel) less the latent heat of the water vapor (heat carried off by water formed by chemical action and passing off as steam).[1] It is simpler to use the lower heat content of fuels than their higher heat content because then the value of the latent heat of water vapor will not have to appear in the remainder of the calculations. All values in fuel calculations are based on standard atmospheric temperature and pressure, which are usually 62 deg. Fahr. and 14.7 lb. per sq. in.

When the lower heating value of a fuel is not known it may be calculated by the following method: Suppose that it is desired to calculate the lower heating value of the carburetted water gas in Table 2, which was given in Chapter II and is to be found on page 31. From this table, the combustible constituents of 1 cu. ft. of the gas are 0.352 cu. ft. of hydrogen, 0.148 cu. ft. of methane, 0.339 cu. ft. of carbon monoxide, and 0.128 cu. ft. of ethylene. The lower and higher heating values of various combustible gases, per cubic foot at 62 deg. Fahr., are given in Table 11.

Using the lower heating values, the heat in the combustible constituents of the carburetted water gas will be:

$$
\begin{array}{rlrr}
H_2 & - \ 0.352 \text{ cu. ft.} \times & 281 = & 99 \\
CH_4 & - \ 0.148 \qquad\qquad \times & 913 = & 135 \\
CO & - \ 0.339 \qquad\qquad \times & 322 = & 109 \\
C_2H_4 & - \ 0.128 \qquad\qquad \times & 1504 = & 192 \\
\hline
 & & & 535 \text{ B.t.u./cu. ft. of fuel gas.}
\end{array}
$$

For the calculation of solid and liquid fuels, the heat content of carbon is required; this is 14,650 B.t.u. per lb.

[1] See *Mechanical Engineers' Handbook*, by Marks, *page 364*.

TABLE 11

PROPERTIES OF SIMPLE GASES

Gas	Chemical Symbol	Approximate Molecular Weight	Cubic Feet of Cold Combustion Air Required per Cubic Foot of Gas	Cubic Feet of Cold Oxygen Required per Cubic Foot of Gas	Heating Value, B.t.u. per Cubic Foot of Gas at 62 Deg. Fahr.		Density, Pounds per Cubic Foot at Atmospheric Pressure and 62 Deg. Fahr.	Specific Heat per Pound at Constant Pressure, Average
					Higher	Lower		
Combustible Gases								
Carbon monox..	CO	28	2.38	0.5	322	322	.0734	.243
Hydrogen.....	H_2	2	2.38	0.5	329	281	.0053	3.42
Methane......	CH_4	16	9.52	2.0	1003	913	.0421	.593
Ethane........	C_2H_6	30	16.70	3.5	1755	1619	.0790	
Propane.......	C_3H_8	44	23.8	5.0	2501	2322	.1158	
Butane........	C_4H_{10}	58	31.0	6.5	3242	3020	.1526	
Ethylene......	C_2H_4	28	14.3	3.0	1591	1504	.0737	.400
Propylene.....	C_3H_6	42	21.4	4.5	2356	2226	.1105	
Butylene......	C_4H_8	56	28.6	6.0	3076	2902	.1473	
Acetylene......	C_2H_2	26	11.9	2.5	1477	1437	.0684	.350
Inert Gases								
Air..........	....	29	....	....	....	....	.0761	.241
Water vapor...	H_2O	18	....	....	....	....	.0473	.481
Oxygen.......	O_2	32	....	....	....	....	.0840	.217
Nitrogen......	N_2	28	....	....	....	....	.0737	.247
Nitric oxide...	NO	30	....	....	....	....	.0789	.231
Carbon dioxide	CO_2	44	....	....	....	....	.1156	.210
Nitrous oxide..	N_2O	44	....	....	....	....	.1157	.221
Sulphur dioxide	SO_2	64	....	....	....	....	.1684	.154

2. Sensible Heat in Fuel Due to Preheating.—Solid fuels are not preheated before combustion, and the heat in preheated liquid fuels is so small that it may be neglected, but some gaseous fuels are sufficiently preheated to carry a considerable amount of heat into the furnace. This is particularly noticeable for low-power gases, as, for example, raw producer gas with a lower heat content of 138 B.t.u. per cu. ft. If this gas is preheated to 1100 deg. Fahr., it will have an additional sensible heat of 20 B.t.u. per cu. ft. The value for sensible heat in B.t.u. per cubic foot of gas is obtained by multiplying the weight in pounds of a cubic foot of the gas by the specific heat of the gas in B.t.u. per pound and by the degrees of preheat above atmospheric temperature. The sensible heat in some common gases at various temperatures of preheat is as follows:

Gas	Lower Heat Content	Specific Heat, B.t.u. per Cubic Foot	Sensible Heat from Preheating, B.t.u. per Cubic Foot				
			300 Deg. Fahr.	600 Deg. Fahr.	900 Deg. Fahr.	1200 Deg. Fahr.	1500 Deg. Fahr.
Natural gas	970	.0268	6.4	14.4	22.5	30.6	38.6
Coke-oven gas	425	.0201	4.8	10.9	16.9	23.0	29.0
Raw producer gas	138	.0189	4.5	10.2	15.9	21.6	27.2
Clean producer gas	128	.0191	4.6	10.3	16.1	21.8	27.5
Blast-furnace gas	90	.0185	4.4	10.0	15.5	21.1	26.6
Blue water gas	287	.0181	4.4	9.8	15.2	20.6	26.0
Coal gas	569	.0222	5.3	12.0	18.7	25.3	32.0

The calculation of densities and specific heats of fuel gases is illustrated by the following: Suppose that the density and specific heat are desired for the coke-oven gas given in Table 2. The density will be determined as follows, using all the constituents and data given in Table 11:

	cu. ft. cu. ft. fuel		lb./cu. ft.		lb./cu. ft. fuel
H_2......	−0.53	×	0.0053	=	0.0028
N_2......	−0.121	×	0.0737	=	0.0089
CH_4.....	−0.281	×	0.0421	=	0.0118
CO......	−0.06	×	0.0734	=	0.0044
CO_2.....	−0.008	×	0.1156	=	0.0009
	Density of fuel			=	0.0288 lb./cu. ft.

The specific heat of the fuel gas will be:

	lb./cu. ft. fuel		specific heat/lb.		B.t.u.
H_2......	0.0028	×	3.42	=	0.0096
N_2......	0.0089	×	0.247	=	0.0022
CH_4.....	0.0118	×	0.593	=	0.0070
CO......	0.0044	×	0.243	=	0.0011
CO_2.....	0.0009	×	0.210	=	0.0002
	0.0288				0.0201 B.t.u./cu. ft.

The average specific heat per pound of the fuel is then

$$\frac{0.0201}{0.0288} = 0.70 \text{ B.t.u./lb.}$$

The specific heats given in Table 11 are average values, and the true value will vary with different temperatures, but the average values are within practical limits for the calculation of sensible heat content. Accurate values of Cp (specific heat at constant pressure is used in all furnace calculations) are given in Marks' *Mechanical Engineers' Handbook*, page 366.

3. Sensible Heat in Combustion Air Due to Preheating.—This value is the sensible heat in air for combustion which has been preheated, before entering the furnace, by means of recuperators or regenerators. The determination of this figure requires a knowledge of the amount of air required per unit of fuel for

combustion, the specific heat of the air, and the temperature of preheat. For most practical purposes (except for blast-furnace gas and producer gas containing large proportions of inert nitrogen gas), the amount of air required for perfect combustion of any fuel can be estimated by figuring one cubic foot of air required for every 100 B.t.u. in the heat content of the fuel. The accuracy of this method is indicated by the following comparison with actual air requirements:

Fuel	Heat Content	Actual Air Required	$\frac{\text{B.t.u.}}{100}$
Coal.	14,134 B.t.u. per lb.	137 cu. ft. per lb.	141
Fuel oil.	140,000 B.t.u. per gal.	1410 cu. ft. per gal.	1400
Natural gas.	970 B.t.u. per cu. ft.	10.1 cu. ft. per cu. ft.	9.7
Coke-oven gas . . .	425 B.t.u. per cu. ft.	4.08 cu. ft. per cu. ft.	4.25
Coal gas.	569 B.t.u. per cu. ft.	5.51 cu. ft. per cu. ft.	5.69

The sensible heat in the air is equal to the weight of air required (volume × density at 62 deg. Fahr. and 14.7 lb. per sq. in. pressure) multiplied by the product of specific heat of air times degrees of preheat. The exact specific heat of air between zero deg. and T deg. Fahr. is equal to $0.233 + 0.000023\, T$, but the specific heat may be taken as 0.24 B.t.u. per lb. for quick determinations.

The amount of air for combustion of a fuel may be accurately calculated by finding the total of the air required for combustion by all the combustible constituents of the fuel. As examples, let us consider the fuel oil and the raw producer gas given in Table 2.

In finding the air required by fuels containing oxygen, it is easier to find the net amount of oxygen required and to convert this result to air. Carbon requires 31. 8 cu. ft. of O_2 (at standard conditions) per pound for perfect combustion, and the oxygen requirement of hydrogen is given in Table 11, so that, for the fuel oil, the total oxygen is:

$$
\begin{array}{lll}
C\ldots\ldots\ldots & 0.837 \text{ lb. lb. oil} \times 31.8 = & 26.6 \text{ cu. ft. } O_2 \\
H_2\ldots\ldots & \dfrac{0.130 \text{ lb.}}{0.0053 \text{ lb./cu. ft.}} & \\
 & = 24.5 \text{ lb. lb. oil} \times \quad .5 = & \underline{12.3} \\
 & & 38.9 \text{ cu. ft. } O_2\text{/lb. fuel oil} \\
O_2\ldots\ldots & \text{already in fuel} - \dfrac{0.013}{0.084} \quad = & \underline{\quad .2} \\
O_2\ldots\ldots & \text{required, net} & 38.7 \text{ cu. ft./lb. fuel oil}
\end{array}
$$

Air is composed of 21 per cent O_2 and 79 per cent N_2 by volume, and of 23 per cent O_2 and 77 per cent N_2 by weight, so that in this case the volume of air required will be $\dfrac{38.7}{0.21} = 184$ cu. ft. per pound of oil. Since there are 7.55 lb. of this oil to the gallon, the air required per gallon is:

$$7.55 \times 184 = 1410 \text{ cu. ft.}$$

In the case of the producer gas of Table 2, there is no oxygen content and the air may be calculated directly from values in Table 11, as follows:

$$
\begin{array}{llll}
H_2\ldots\ldots & 0.125 \text{ cu. ft./cu. ft. fuel} & \times\, 2.38 = & 0.298 \\
CH_4\ldots\ldots & 0.030 & \times\, 9.52 = & 0.286 \\
CO\ldots\ldots & 0.205 & \times\, 2.38 = & \underline{0.488} \\
 & \text{Total air/cu. ft. fuel} & = & 1.072 \text{ cu. ft.}
\end{array}
$$

The quantities of air given in this section on sensible heat in preheated air are all for perfect combustion. In determining the sensible heat in preheated air, the percentage of excess air must be known or assumed, and included in the calculation, as explained in Item 7.

4. Heat in Material Which Has Been Preheated before Charging.—This item must be considered in cases where the material to be heated has been preheated in another furnace or by exposure to radiation from cooling material. It is frequently

difficult to evaluate accurately if the exact temperature of preheat is not known. If the material has been preheated for a sufficient time to be heated thoroughly, the temperature throughout the material will be slightly less than that of the chamber from which it is taken, while if the time has not been long enough to insure even temperature throughout, an average temperature must be estimated. The heat content of the preheated stock is obtained by multiplying the weight in pounds by the degrees of preheat above atmospheric temperature and the specific heat of the material. The heat contents of iron and steel in B.t.u. per pound above 62 deg., for various temperatures (specific heat × preheat), follow for ready reference:

Preheat temperature, deg. Fahr.	200	400	600	800	1000	1200	1400	1600	1800	2000
Heat content, B.t.u. per lb.	15	42	69	98	129	164	209	244	284	315

Figure 50 shows the values of heat content for steel (same as iron) and for various other metals at all temperatures.

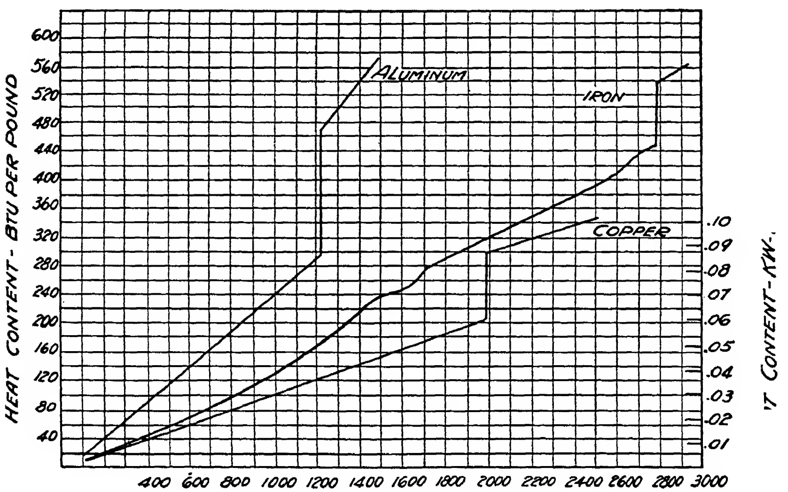


FIG. 50.—Heat Content of Metals.

5. Heat Absorbed by Heating Material in the Furnace.—This value is obtained in the same manner as in the preceding case for preheating, whenever the process is simply heating, as is the case in the usual industrial heating furnace. The temperature used in the calculation is that to which the material is heated to suit the process of which the heating is a part. There are processes, in addition to simple heating operations, which require other considerations, such as the burning and calcining of chemical products, the melting and refining of metals, and the drying of material, which requires heat to convert the moisture into steam and to raise this steam to the temperature of the furnace. The most common types of drying problems are core and mould ovens, and the core oven serves as a good example of additional heat calculation. Dry sand has a specific heat of 0.194, so that each pound of cores heated to 400 deg. Fahr. absorbs:

$$(400 - 62) \times 0.194 = 65.5 \text{ B.t.u.}$$

A pound of core sand contains about 0.06 lb. moisture, which requires:

$$0.06 \times 970 \text{ B.t.u./lb.} = 58.2 \text{ B.t.u.}$$

for conversion to steam. Also, the heat to raise 0.06 lb. steam from 212 deg. Fahr. to 400 deg. Fahr. is

$$0.06 \times 0.47 \text{ (specific heat)} \times 188 \text{ deg.} = 5.3 \text{ B.t.u.}$$

The total heat requirement of each pound of cores will therefore be:

$$65.5 + 58.2 + 5.3 = 129.0 \text{ B.t.u.}$$

All of this is included in useful heat.

6. Heat Equivalent of Waste-heat Boiler Power Developed.—This item represents strictly useful energy because it is conserved to be used outside of the furnace. Its value is the actual

boiler horsepower developed by the waste-heat units attached to the furnace, converted into heat units to agree with the other items in the balance of heat. The thermal equivalent of a boiler horsepower being 33,300 B.t.u. per hour, in the case of a waste-heat boiler delivering 100 H P., 3,330,000 B.t.u. per hour could be credited as useful heat in the heat balance.

7. Sensible Heat Leaving Furnace in Flue Gases.—This is the greatest of the losses in a fuel-fired heating furnace and depends on the amount of flue gases and the temperature at which they leave the furnace *heating chamber*. This temperature is always used in calculation, and if any of the heat in the flue gases is salvaged beyond this point it is represented in the heat balance by the heat input covered in Items 2, 3, or 4; or by the useful heat in the case of waste-heat boiler. This is made clearer by remembering that the heat balance is intended to account for the heat entering and leaving the actual useful heating chamber.

The accurate calculation of this loss is somewhat complicated, but practical values may be readily obtained by simplified methods. The volumes (cold measure, 62 deg. Fahr. and 14.7 lb. per sq. in.) of flue gases produced by perfect combustion with no excess air can be fairly closely figured by allowing 105 cu. ft. of flue gases for each 10,000 B.t.u. in the heat value of the fuel (except in the cases of blast-furnace gas and producer gas). The actual volumes of flue gases and the densities of these gases for industrial fuels are given in Table 2.

Since the products of perfect combustion contain only the theoretical air required, the excess air expected must be added to obtain the total flue gases. This is calculated as a percentage of the theoretical air, obtained as explained under Item 3, and the percentage used will depend on the fuel, burners, and furnace. It is usually about 20 per cent for solid fuels and 10 per cent maximum for liquid and gaseous fuels. The mean specific heat for all flue gases is about 0.27 B.t.u. per lb., and the heat in the gases is obtained by multiplying the product of the cubic feet of gas per unit of fuel and the density by the product

of the specific heat and the leaving temperature less 62 deg. Fahr. The leaving temperature must usually be assumed, as it is difficult to calculate accurately, because it will vary with the rate at which the furnace is forced. In batch-type furnaces it varies from 50 to 300 deg. above the final temperature of the heated material; and in continuous furnaces in which the gases leave at the charging end where the cold material enters, it ordinarily varies from 1000 to 1500 deg. Fahr., and may be as high as 1800 deg. Fahr. for large billet furnaces when forced hard. This value can be estimated closely only from some experience with furnaces of various kinds.

As an example of the calculation of the sensible heat in flue gases, suppose that it is desired to know the heat contained in the flue gases from one gallon of oil leaving the furnace at a temperature of 1500 deg. Fahr. and burned with 10 per cent excess air. One gallon of the oil given in Table 2 will produce 1505 cu. ft. of flue gases, or 114 lb. (0.0760 lb. per cu. ft. density). The oil requires 1410 cu. ft. of air per pound for perfect combustion, so that the weight of excess air in the flue gases will be:

$$10 \text{ per cent} \times 1410 \times 0.0761 \text{ (density of air)} = 10.7 \text{ lb.}$$

The heat in the total flue gases will then equal:

$$124.7 \text{ lb.} \times 0.27 \text{ (specific heat)} \times (1500 \text{ deg. Fahr.} - 62 \text{ deg. Fahr.}) = 48{,}500 \text{ B.t.u./gal. of fuel oil.}$$

Figure 51 is a graphical representation of the heat in the flue gases of perfect combustion and of the heat in air required for perfect combustion of coal gas. This figure supplements the series of such charts given in W. Trinks' *Industrial Furnaces*, Vol. I, for all other common fuels.

The exact calculation of the flue gases produced by perfect combustion of fuels is illustrated by the following example for bituminous coal of analysis given in Table 2:

The products of perfect combustion of a fuel, neglecting

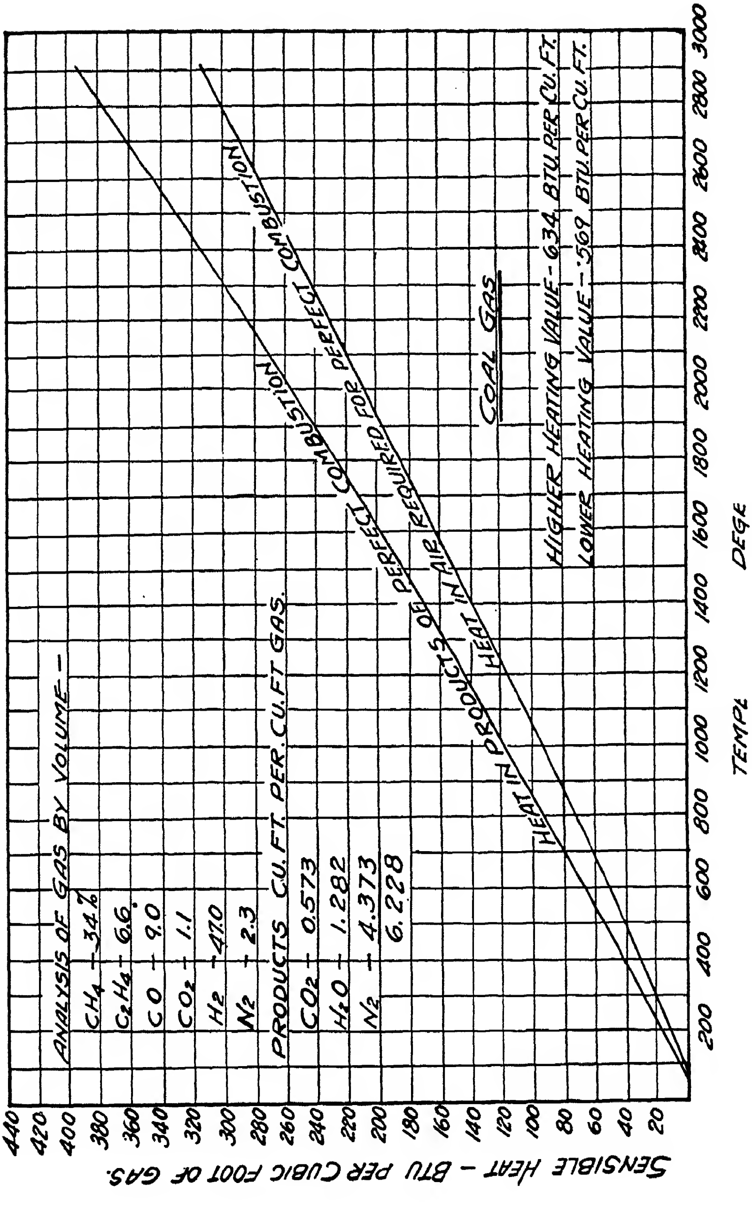


FIG. Heat in Combu G

sulphur in the fuel, are carbon dioxide, water vapor, and nitrogen, and they are determined as follows, per pound of coal:

$$\begin{array}{llll} C + O_2 = & CO_2 & & \\ 12 \quad 32 & 44 & \text{molecular weights} \end{array}$$

$$\begin{array}{llll} 2H_2 + O_2 = & 2H_2O & & \\ 4 \quad 32 & 36 & \text{molecular weights} \end{array}$$

Then

	Pounds		Per Pound of Coal
...—0.78 C in coal$\times \frac{44}{12}$	= 2.86;	$\frac{2.86}{0.1156}$ =	24.8 cu. ft. CO_2
H_2O —0.052 H_2 in coal$\times \frac{36}{4}$	= 0.47;	$\frac{0.47}{0.0473}$ =	10.0 cu. ft. H_2O
N_2 from coal	= 0.01;	$\frac{0.01}{0.0737}$ =	0.1 cu. ft. N_2
N_2 from air—137 cu. ft. air per lb. coal (Table 2) $\times$ 79 per cent$\times$0.0737	8.0	8	108.0 cu. ft. N_2
	11.34,	0.0737 =	142.9

The volume of flue gases per pound of coal is, therefore, 143 cu. ft., and the density of these gases is:

$$\frac{11.34}{142.9} = 0.079 \text{ lb./cu. ft.}$$

Similar calculations are made in the determination of the flue gases resulting from the combustion of gaseous fuels. As an example, the following calculations are for the natural gas of Table 2:

$$\begin{array}{lllll} CH_4 + & 2O_2 = & CO_2 & + 2H_2O & \\ 16 & 64 & 44 & 36 & \text{molecular weights} \end{array}$$

$$\begin{array}{lllll} 2C_2H_6 + & 7O_2 = & 4CO_2 & + 6H_2O & \\ 60 & 224 & 176 & 108 & \text{molecular weights} \end{array}$$

Then the products per cubic foot of natural gas are:

	Cubic Feet	Pounds		Cubic Feet
CO_2	$- 0.803\ CH_4 \times 0.0421 \times \frac{44}{16}$	$= 0.093;$	$\frac{0.093}{0.1156}$	$= 0.805\ CO_2$
	$0.147\ C_2H_6 \times 0.0790 \times \frac{176}{60}$	$= 0.034;$	0.1156	$0.294\ CO_2$
H_2O	$0.803\ CH_4 \times 0.0421 \times \frac{36}{16}$	$= 0.076;$	$\frac{0.076}{0.0473}$	$= 1.603\ H_2O$
	$0.147\ C_2H_6 \times 0.0790 \times \frac{108}{60}$	$= 0.021;$	$\frac{0.021}{0.0473}$	$0.442\ H_2O$
N_2	from fuel $- 0.05 \times 0.0737$	$= 0.004;$		$= 0.050\ N_2$
N_2	$- 10.11$ cu. ft. air/cu. ft fuel $\times$ 79 per cent $\times 0.0737$	$= 0.590,$	$\frac{0.59}{0.0737} -$	$8.000\ N_2$
		0.818		11.194

The volume of flue gases from perfect combustion of this natural gas is 11.19 cu. ft., and the density of the flue gases is:

$$\frac{0.818}{11.19} = 0.0730 \text{ lb./cu. ft.}$$

8 and 9. Radiation and Heat Absorbed by Furnace Walls.—These two items are usually considered separately, but the author believes that the calculation can be simplified and better practical results obtained by combining the factors, if the correct relationships between them can be established. The usual method, except in the case of car-type furnaces charged cold and cooled before the charge is withdrawn, is to consider the furnace walls up to temperature and soaked with heat before the material is charged at the beginning of the day; but this method usually results in theoretical values that are much lower than can be obtained in practice. The reason appears to lie in the fact that most furnaces that are not operated twenty-four hours per day never do reach absolute equilibrium conditions, so that in addition to radiation there is heat being con-

stantly absorbed by the walls. The experimental data from which definite conclusions can be derived are scarce, but, from observations and calculations by the writer, Fig. 52 has been

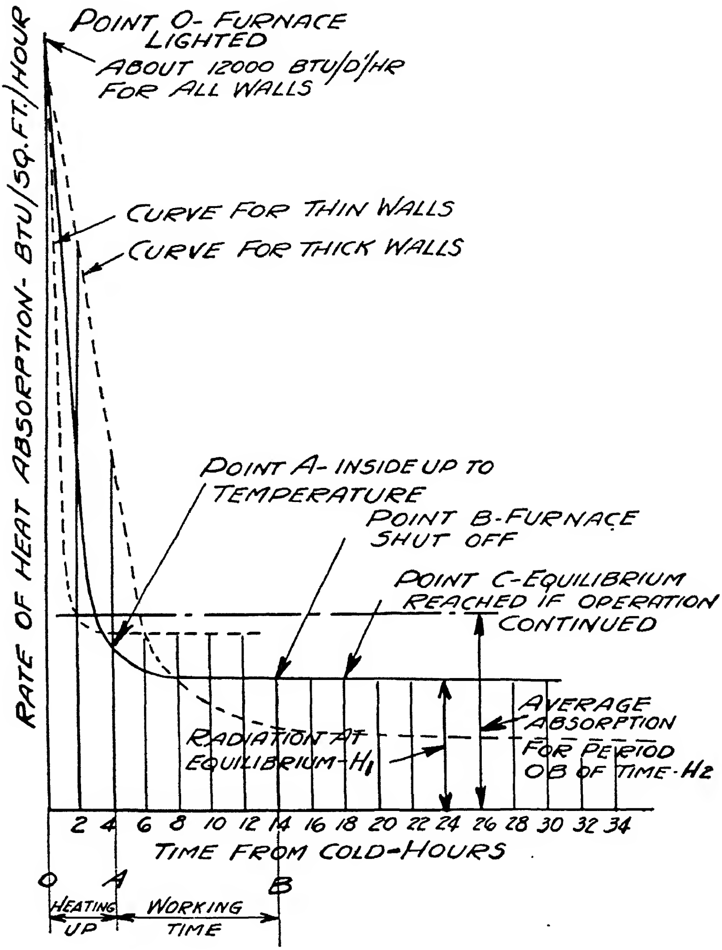


Fig. 52.—Rate of Heat Absorption in Furnace Walls.

prepared to show the conditions which exist in industrial furnace refractories with respect to heat absorption and time. The heating process when a furnace is lighted is as follows:

The transfer of heat from flame or electrical resistors to the

refractories is at first very rapid because of the great temperature difference between the heat source and the cold walls or other refractories. This transfer of heat is so rapid at first that in the case of fuel-fired furnaces there is a tendency to cool the fuel below the ignition temperature, and it is difficult to keep the burners lighted. The refractory immediately around the burners heats up very rapidly, however, and this helps ignition, but the walls continue to soak up greedily most of the heat developed. This continues for a comparatively short period of time, depending upon the size of the furnace, because the refractories absorb heat faster than they are able to conduct it to their interiors, and the temperature builds up at the surface. This gain in temperature at the surface reduces the temperature difference between the flame and the refractories, and the rate of heat transfer into the wall drops accordingly until point *A* of Fig. 52 is reached, when the inside surface of the furnace is up to temperature. Material is usually charged into the furnace at this point, and the temperature conditions through the wall will be somewhat as shown in curve *A* of Fig. 53, although the shape of this curve will vary somewhat with the thickness of the wall.

Somewhere near the time that the walls are reaching temperature on the inside, they commence to radiate heat from the outside, and the heat entering the wall is then partly absorbed and partly radiated. This continues until a point of equilibrium, marked *C* in Fig. 52, is reached, when the wall has absorbed all the heat it will hold and the amount of heat entering is just equal to the amount radiated. The temperatures through the wall are then somewhat as shown in curve *C* of Fig. 53. For all but very thin walls, however, the daily period of ten to twelve hours of operation of the furnace lies somewhere within a section as represented by *AB* in Fig. 52, and the temperature conditions are somewhere between curve *A* and curve *B* of Fig. 53. This condition is entirely too complicated to be represented mathematically for practical purposes, but the values of H_1, the radiation in B.t.u. per square foot at equilibrium conditions, can be pretty well determined. Then all that is needed is the ratio, experimentally determined, between this value H_1 and the

unknown value of H_2 which represents the average heat of both absorption and radiation from the section *OB* of the curve of Fig. 52. If this ratio can be determined and is multiplied by the proper value of H_1 for a particular wall construction, the product will be the average heat which enters the wall on the furnace side per hour from the time that the furnace is lighted until a time ten or twelve hours after the first material has been charged.

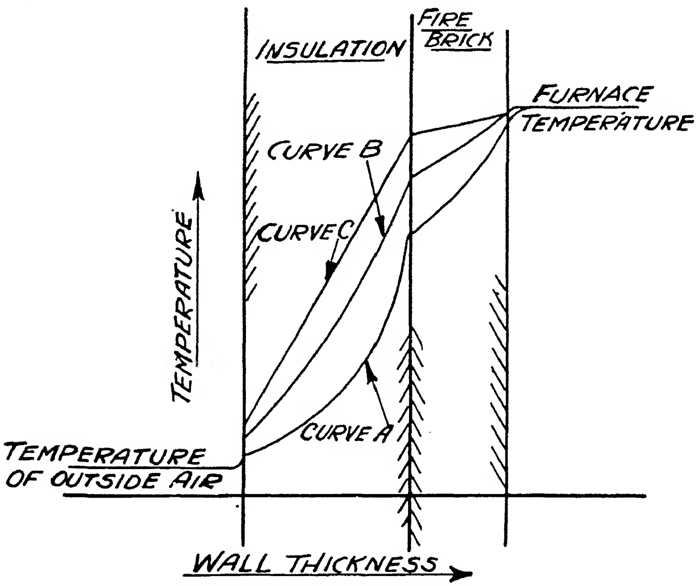


Fig. 53.—Temperature Distribution in Furnace Walls (see Fig. 52).

Table 12 gives values of H_1 for various conditions of temperature and wall construction. These values are higher than theoretical, but they give very satisfactory results in practice and take care of all losses, such as joints, shrinkage, and other items, which the theoretical values neglect.

These values may be used directly in those cases where the furnace is maintained at temperature continuously day and night for a period of a week at a time, because the refractories have been thoroughly soaked and equilibrium conditions are reached in the first day or so, as the thickest ordinary walls will

TABLE 12

HEAT LOSSES THROUGH VARIOUS FURNACE WALLS, B.T.U. PER SQUARE FOOT PER HOUR

Firebrick, Inches	Insulation, Inches	Furnace Temperature, Deg. Fahr.						
		1000	1200	1400	1600	1800	2000	2200
4½	0	1050	1250	1480	1860	2130		
	2½	450	510	600	720	850	1005	
	5	216	300	375	450	530	610	
	7½	178	215	265	315	362	410	
	10	150	185.	220	260	295	330	
	12½	140	165	190	220	250	280	
9	0	550	700	860	1040	1220	1400	1600
	2½	310	380	460	560	660	762	865
	5	204	244	269	339	364	429	490
	7½	170	200	232	266	300	334	370
	10	140	170	199	226	253	281	310
	12½	125	150	170	190	212	235	260
13½	0	405	500	590	700	830	975	1120
	2½	230	300	380	455	535	615	705
	5	166	204	244	259	314	349	396
	7½	150	175	200	226	255	285	320
	10	128	150	176	200	228	254	280
18	0	264	365	460	560	660	760	865
	2½	180	239	267	319	367	455	515
	5	149	181	215	247	280	311	349
	10	127	148	170	194	220	240	270

reach this point in thirty hours of operation. They also apply directly for the short operating periods of thin walls of 4½ in. of firebrick without insulation because the wall has reached equilibrium before the section *AB* in Fig. 52 commences. For these conditions, the value of the ratio H_1 to H_2 is 1.0, but in the majority of instances the walls are absorbing heat in addition to radiating it, and the values of radiation must be multiplied by a con-

stant to give practical results. Table 13 gives these values, which were calculated as accurately as possible and then checked with actual practice results in an effort to fix them so that results obtained by their use would be practical. It must be remembered that the ratios of Table 13 are to be used in cases where the operation is not continuous day and night, and that they must be used in conjunction with Table 12. For continuous twenty-four-hour operation, the values of Table 12 may be used directly to obtain all the heat entering the walls, except in the case of electric furnaces, where the values of Table 12 should be multiplied by 2.0 in all cases. For ten- to twelve-hour operation, the ratios of Table 13 are applicable to electric furnaces as well as to fuel-fired furnaces.

TABLE 13

RATIOS OF H_1 TO H_2 TO BE USED WITH TABLE 12 WHEN FURNACE OPERATING PERIOD DOES NOT EXCEED 12 HOURS PER DAY

(See Text)

Wall Construction		Ratio
Firebrick, Inches	Insulation, Inches	
$4\frac{1}{2}$	0	1
$4\frac{1}{2}$	5	$1\frac{1}{4}$
$4\frac{1}{2}$	10	3
9	0	2
9	5	$2\frac{1}{2}$
9	10	3
$13\frac{1}{2}$	0	3
$13\frac{1}{2}$	5	$3\frac{1}{2}$
$13\frac{1}{2}$	10	4
18	0	4
18	5	$4\frac{1}{2}$

As an example of the method of calculation, suppose that it is desired to determine the average amount of heat lost to the walls of a furnace per hour if the temperature is 2200 deg. Fahr. and the walls are built of 18 in. of firebrick with no insulation. The furnace is lighted at 2 A.M., charged at 7 A.M., and shut down at 5 P.M. Table 12 gives the radiation at equilibrium as about 865 B.t.u. per sq. ft. per hour for these conditions. The ratios in Table 13 are independent of temperature, and for these conditions the ratio will be 4. The average heat transmitted to the walls from 2 A.M. until 5 P.M. is, therefore:

$$4 \times 865 = 3460 \text{ B.t.u./hour.}$$

10. Heat to Conveyors, Containers, or Cars.—The problem involved in the evaluation of this item may be one of two kinds. The conveyor may be cold when charged, as in the usual case of pans in which the material to be heated is pushed through the furnace and carburized in alloy boxes; or the conveyor may enter the furnace again before losing all of its heat, as in the case of continuous chain conveyors. In order that the conveyed material may be uniformly heated, it is evident that the conveying holder, whether box or chain, must also be thoroughly heated to the same temperature, so that the first condition is quite simple. The heat absorbed by the conveyor is simply the weight of the conveyor multiplied by the heat content of one pound of the metal from which the conveyor is made at the final temperature to which it is heated. This heat content can be considered the same for high-temperature alloys as for steel, and values for various temperatures are given under Item 4, discussed previously. The difficulties in the case of a conveyor that already contains some heat are the same as in Item 4, because the temperature of the conveyor as it enters the furnace cannot be accurately foretold. Experience will make an accurate guess possible, but in any case a safe method is to assume that the conveyor temperature is one-fourth of the furnace temperature. The heat absorbed will then be the product of the weight of the conveyor passing through the furnace per hour multiplied by the

difference in heat content per pound at the furnace temperature, and at one-fourth of the furnace temperature. Refractory car bottoms are considered as furnace walls and come under Items 8 and 9, already considered.

11. Heat to Water in Water-cooled Parts.—In large furnaces at high temperatures, the heat absorbed by the water in water-cooled rails and parts frequently amounts to 5 per cent of the fuel used and is an item worth considering. The principle of water cooling is that the water passing through the water-cooled part absorbs sufficient heat to keep the part cool enough to retain its strength and resist abrasion or other action. Heat is constantly absorbed and transmitted to the water flowing through the part because there is a constant temperature difference between the furnace and the part, which always means heat flow by radiation from the higher to the lower temperature. A method of calculating this loss is to determine the square inches of water-coöled metal actually exposed to the furnace temperature and the temperature at which the part may be safely maintained. Then the area of the surface multiplied by the difference in black-body radiation (radiation may not be 100 per cent of black body, but can be said to be in this case for practical purposes) for the temperature of the furnace and the temperature of the water-cooled part will give the amount of heat transmitted to the water-cooled part. Black-body radiation, which means radiation under conditions of perfect reflection from all sides (as in the case of the interior of a hot furnace) is given for various temperatures in Fig. 54. As an example of this calculation, suppose that it is desired to obtain the loss to 40 ft. of $2\frac{1}{2}$-in. diameter XX heavy water-cooled pipe, half imbedded in brickwork so that one-half of the circumference is exposed to the heat of a furnace at 2500 deg. Fahr. The area exposed will be:

$$\tfrac{1}{2} \times 9.03 \times 40 \times 12 = 2160 \text{ sq. in.}$$

The wear on these pipes would not be excessive if the temperature did not exceed 700 deg. Fahr. Radiation at 2500 deg. Fahr. is 850

B.t.u. per sq. in. per hour, and at 700 deg. Fahr. it is 10 B.t.u. per sq. in. per hour. The heat transmitted is:

$$2160 \times (850 - 10) = 1{,}810{,}000 \text{ B.t.u./hour.}$$

The amount of water required is the amount which will absorb this heat in a temperature rise from atmospheric temperature to about 180 deg. Fahr. It should not be higher than this

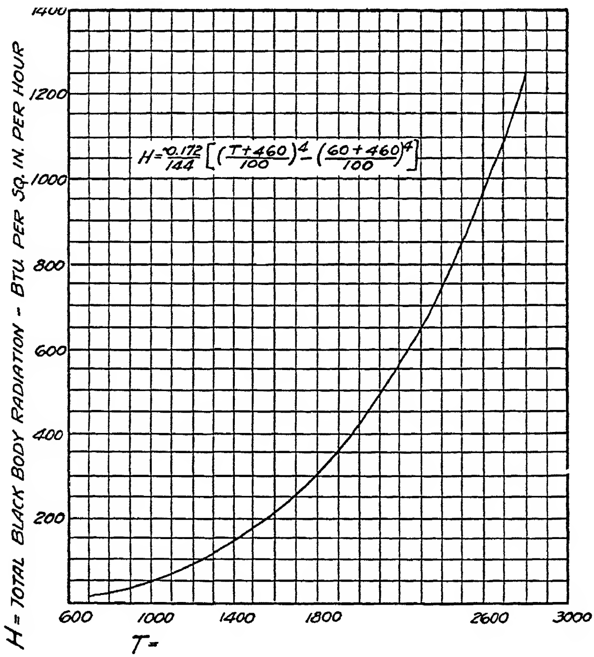


FIG. 54.—Variation of Black Body Radiation with Temperature.

temperature, to avoid steam formation which can become pocketed and allow the pipe to burn out.

12 and 13. Heat Lost through Doors and Openings and Heat Lost in Unburned Fuel.—These items can be accurately calculated, but for all practical purposes the results are hardly worth the effort involved. For some special cases, there is an advantage in knowing these items, but for practical estimation of fuel consumption they can be satisfactorily covered by adding 10 to 20

per cent to the consumption obtained by calculating the various items as described above. The amount to be added varies with the size of the doors, the amount of time that they are opened, etc.

The method of accurately calculating the unburned-fuel loss, represented by the presence of CO in the flue gases, is given in the following paragraph,[2] and the determination of radiation losses is considered further in Chapter IX. Values for the loss in unburned fuel for different combustion conditions and for fuels from Table 2 are given in Table 14.

The method of calculating the losses in Table 14 is illustrated by the following: Suppose that in the flue gases resulting from combustion of the natural gas of Table 2, there is 2 per cent CO, and O_2 corresponding to 10 per cent excess air. The formula for heat lost due to CO content is:

$$L = 10150 \times C \frac{\text{per cent CO}}{\text{per cent CO} + \text{per cent CO}_2}$$

where L = B.t.u. lost/unit fuel;

C = weight of C in fuel.

The figure 10150 is the B.t.u. difference in heat evolved in burning one pound of carbon to CO_2 and to CO.

Then, in the natural gas fuel, the carbon occurs in CH_4 and in C_2H_6.

The fraction by weight of C in CH_4 is:

$\frac{12}{12 + (4 \times 1)}$ 0.75 (ratio molecular weights) and in C_2H_6 is:

$$\frac{2 \times 12}{(2 \times 12) + (6 \times 1)} = 0.80.$$

[2] For further discussion, see *Industrial Furnaces*, Vol. I, by W. Trinks.

TABLE 14

LOSSES DUE TO POOR COMBUSTION, B.T.U. LOST PER UNIT OF FUEL BURNED*

Fuel	Lower Heating Value, B.t.u. per Unit	CO in Flue Gases, Per Cent	Excess Air in Flue Gases, Per Cent				
			−10	0	10	20	30
Coal	14,134	1	450.	500.	545.	595.	640.
		2	900.	1000.	1090.	1190.	1280.
		3	1350.	1500.	1635.	1785.	1920.
		4	1800.	2000.	2180.	2380.	2560.
Oil	140,000	1	580.	640.	695.	755.	815.
		2	1160.	1280.	1390.	1510.	1630.
		3	1740.	1920.	2085.	2265.	2445.
		4	2320.	2560.	2780.	3020.	3260.
Natural gas	970	1	32.	36.	39.	42.	46.
		2	65.	72.	78.	84.	92.
		3	96.	108.	117.	126.	138.
		4	128.	144.	156.	168.	184.
Coke-oven gas	425	1	13.5	15.0	16.5	17.5	19.0
		2	27.0	30.0	33.0	35.0	38.0
		3	40.5	45.0	49.5	52.5	57.0
		4	54.0	60.0	66.0	70.0	76.0
Clean producer gas	128	1	4.0	4.3	4.5	4.7	5.0
		2	8.0	8.6	9.0	9.4	10.0
		3	12.0	12.9	13.5	14.1	15.0
		4	16.0	17.2	18.0	18.8	20.0
Coal gas	569	1	18.0	19.6	21.4	23.2	24.8
		2	36.0	39.2	42.8	46.4	49.6
		3	54.0	58.8	64.2	69.6	74.4
		4	72.0	78.4	85.6	92.8	99.2
Blue water gas	287	1	8.5	9.3	10.0	10.8	11.5
		2	17.0	18.6	20.0	21.6	23.0
		3	25.5	27.9	30.0	32.4	34.5
		4	34.0	37.2	40.0	43.2	46.0
Carburetted water gas	535	1	16.0	17.6	19.0	20.5	21.9
		2	32.0	35.2	38.0	41.0	43.8
		3	48.0	52.8	57.0	61.5	65.7
		4	64.0	70.4	76.0	82.0	87.6

* Units are pounds for coal, gallons for oil, and cubic feet for

Then, from the analysis of the gas in Table 2,

$$CH_4 - 0.803 \text{ cu. ft./cu. ft. fuel}$$
$$\times 0.0421 \text{ lb./cu. ft.} \times 0.75 = 0.0253 \text{ lb. carbon}$$
$$C_2H_6 - 0.147 \text{ cu. ft./cu. ft. fuel}$$
$$\times 0.0790 \text{ lb./cu. ft.} \times 0.80 = \underline{0.0093}$$
$$0.0346 \text{ lb. carbon in 1 cu. ft. fuel}$$

Then, since both CO and CO_2 burn to the same volume from the same weight of carbon, the term, per cent CO + per cent CO_2, will always equal the per cent CO_2 from perfect combustion, which is the simplest to calculate. In this case, it has already been determined under Item 7 and equals 1.10 cu. ft. CO_2 per cubic foot natural gas burned with perfect combustion. From Table 2, the volume of products of perfect combustion is 11.19 cu. ft., and the air required is 10.11, so that the products from combustion with 10 per cent excess air are:

$$11.19 + \frac{10.11}{10} = 12.20,$$

and the term, per cent CO_2 + per cent CO is:

$$\frac{1.10}{12.20} \times 100 = 9.0,$$

$$L = 10150 \times 0.0346 \times 0.22 = 78.0 \text{ B.t.u. lost/cu. ft. natural gas.}$$

The heat lost for other conditions may be readily obtained from the actual losses given in Table 14.

This completes the detailed consideration of the different items entering into the estimation of fuel consumption, and these will now be illustrated by several practical examples.

Examples of Fuel Consumption: *Example 1, Rolling Mill Furnace, Batch Type.*

Construction.—Furnace chamber 22 ft. long by 8 ft. deep by $2\frac{1}{2}$ ft. high to the skew of the arch. Roof of 9 in. of firebrick, wall of 18 in. of firebrick,

and hearth of $13\frac{1}{2}$ in. of firebrick. Seven small doors along the front of the furnace. Material handled in and out of the furnace by monorail tongs.

Operation.—Furnace lighted at 2 A.M. and first charge put in at 7 A.M. Twenty-five tons of 4-in. × 4-in. billets heated to 2200 deg. Fahr. in the 12-hour period until 7 P.M.

Calculation.—Heat to billets per hour = 25 tons × 2000 B.t.u. lb. × 340 B.t.u. per lb. = 1,420,000

Heat to walls per hour:

			(Table 12)		(Table 13)		
Roof....	22 ft. × 9 ft.	×	1600	×	2		634,000
Walls...	2 ft. × $2\frac{1}{2}$ ft. × 8	×	865	×	4		138,000
Walls...	2 ft. × $2\frac{1}{2}$ ft. × 22	×	865	×	4	=	380,000
					(Neglecting doors)		
Hearth..	22 ft. × 8 ft. ×	×	1120	×	3	=	590,000

Total B.t.u. per hour absorbed (average from 2 A.M. to 7 P.M.) 1,742,000

Heat in flue gases:

The fuel used is oil having a lower heat content of 127,000 B.t.u. per gal. By the method given in Item 7, the quantity of flue gases per gallon is calculated as 1170 cu. ft. (cold measure) with a density of 0.0803 lb. per cu. ft. The weight of flue gases is therefore:

$$1170 \times 0.0803 = 94 \text{ lb. per gal. of oil.}$$

The leaving temperature of the flue gases is the same as that of the furnace, which will be about 200 deg. above the final temperature of the steel for average rate of heating, or 2400 deg. Fahr. The heat in the products of perfect combustion of a gallon of oil as they leave the furnace will then be:

$$94 \text{ lb.} \times 0.27 \text{ specific heat} \times (2400 - 62) = 59{,}500 \text{ B.t.u.}$$

In addition to this, the heat in the excess air must be considered. If the percentage of excess air is assumed to be 10 per cent, the heat in this excess air will be (see Item 3):

$$1270 \text{ cu. ft.} \times 0.0761 \text{ lb. per cu. ft.} \times 10 \text{ per cent} \times 0.24 \text{ specific heat} \times (2400 - 62) = 5400 \text{ B.t.u. per gal. of oil.}$$

The total heat carried off by the flue gases is then:

$$59{,}500 + 5400 \text{ B.t.u.} = 64{,}900 \text{ B.t.u. per gal. of oil,}$$

and the heat remaining in the furnace for useful heat and other losses is:

$$127{,}000 - 64{,}900 = 62{,}100 \text{ B.t.u. per gal.}$$

The gallons of oil required for heat to billets and to walls is:

$$\frac{1{,}420{,}000 + 1{,}742{,}000}{62{,}100} = 51 \text{ gal. of oil per hour.}$$

In this case the doors are kept open a considerable amount of the time while billets are charged and discharged, and the addition for other losses, as covered under Items 12 and 13, should be 20 per cent. The calculated fuel consumption will then be:

$$1.20 \times 51 = 61.2 \text{ gal. oil per hour.}$$

The oil consumption actually measured on this furnace was 65 gal. per hour.

Example 2, Car-Type Furnace.

Construction.—The inside dimensions of the furnace are 15 ft. long by 8 ft. wide by 3 ft. high. The roof is of 9 in. of firebrick covered by $2\frac{1}{2}$ in. of insulation. Sidewalls are of 18 in. of firebrick; door, 8 ft. wide by 3 ft. high with 7 in. of rammed lining, and car bottom of $13\frac{1}{2}$ in. of firebrick and $2\frac{1}{2}$ in. insulation. The fuel is fuel oil.

Operation.—Ten tons of castings are charged on the car, and the furnace brought up to a temperature of 1650 deg. Fahr. The temperature is held at that point until the heat is shut off. Total heating time with fuel on is 8 hours.

Calculation.—Heat to castings per hour, average:

$$\frac{10 \text{ tons} \times 2000 \times 250 \text{ B.t.u. per pound}}{8 \text{ hours}} = 625{,}000 \text{ B.t.u.}$$

Heat to walls per hour, average:

					B.t.u. per Square Foot per Hour (Table 12)			(Table 13)		B.t.u.
Roof......	15 ft.	×	9 ft.	×	600		×	$2\frac{1}{4}$	=	182,000
Sides......	15 ft.	×	3 ft.	×	600	× 2	×	4	=	216,000
Rear......	8 ft.	×	3 ft.	×	600		×	4	=	57,600
Door......	8 ft.	×	3 ft.	×	1000		×	2	=	48,000
Car.......	15 ft.	×	8 ft.	×	500		×	$3\frac{1}{4}$	=	195,000
Total heat to refractories per hour, average............										698,600

Heat in flue gases: By the same method as in the preceding example, the heat in the products of perfect combustion of fuel oil when leaving the furnace at about 1800 deg. Fahr. is 44,500 B.t.u. per gal., and that in 10 per cent excess air at the same temperature is 4140 B.t.u. per gal., so that

the total heat loss per gallon is 48,640 B.t.u. The heat remaining for the same grade of oil as in the preceding example is then:

$$127{,}000 - 48{,}640 = 78{,}360 \text{ B.t.u. per gallon.}$$

and the gallons required to heat the castings and walls are:

$$\frac{625{,}000 + 698{,}600}{78{,}360} = 16.9 \text{ gal. per hour.}$$

Since the door in this furnace is kept closed for the entire time, the miscellaneous losses will not exceed 10 per cent. The fuel consumption is then:

$$1.10 \times 16.9 = 18.6 \text{ gal. of oil per hour.}$$

The actual measured consumption of oil on this furnace was 17.50 gal. of oil per hour.

Example 3, Small Continuous Furnace.

Construction.—An alloy conveyor is enclosed in this furnace at the discharge end and extends outside the furnace at the charging end. The dimensions of the furnace inside are 8 ft. long by 15 in. wide by 16 in. high. The roof is of 3 in. of firebrick tile, the walls of $4\frac{1}{2}$ in. of firebrick with $1\frac{1}{4}$ in. of insulation. The bottom is the same as the walls. The weight of the conveyor is 8 lb. per ft., and the fuel is artificial gas (coal gas).

Operation.—Two hundred pounds of small steel parts are heated per hour in this furnace to a temperature of 1600 deg. Fahr. They are carried through the furnace on the conveyor, which travels at a speed of 2 ft. per minute.

Calculation.—Heat to steel parts per hour, average 200 lb. × 244 B.t.u. per pound = 48,800 B.t.u.

Heat to conveyor per hour (see Item 10).

Assuming the temperature of the conveyor to be one-fourth of that of the final temperature of the steel, when it reenters the furnace, the temperature will be:

$$\tfrac{1}{4} \times 1600 = 400 \text{ deg. Fahr.}$$

Heat content per pound at 1600 deg. Fahr. is 244 B.t.u.
Heat content per pound at 400 deg. Fahr. is 42 B.t.u.

Difference.......................... 202 B.t.u.

Heat absorbed per hour equals 2 ft. per min. × 60 × 8 lb. per ft. × 202 B.t.u. per pound = 193,900 B.t.u.

Heat to walls per hour, average:

	B.t.u. per Square Foot per Hour (Table 12)					(Table 13)	B.t.u.
Roof......	8 ft.	×	$1\frac{1}{4}$ ft.	×	2600	× 1	26,000
Sides......	18 ft.	×	1 ft.	×	1300	× 1	31,000
Bottom....	8 ft.	×	$1\frac{1}{4}$ ft.	×	1300	× 1	13,000
Total heat to walls per hour.							70,000

Heat in flue gases: By the same method as before, the heat in the products of perfect combustion per cubic foot of coal gas, when leaving at a temperature of 1700 deg. Fahr., is:

$$4.93 \text{ cu. ft.} \times 0.0785 \text{ lb. per cu. ft.} \times 0.27 \text{ specific heat} \times (1700 - 62) = 171 \text{ B.t.u. per cu. ft. of gas.}$$

The heat in 10 per cent of excess air is:

$$5.5 \text{ cu. ft.} \times 0.0761 \text{ lb. per cu. ft.} \times 0.25 \text{ specific heat} \times (1700 - 62) = 17.2 \text{ B.t.u. per cu. ft. of gas,}$$

and the total heat carried out by the flue gases per cubic foot of gas is 188.2 B.t.u. The heat available in the furnace is, therefore:

$$560 \text{ (lower heat content)} - 188.2 = 371.8 \text{ B.t.u. per cu. ft.}$$

The cubic feet of gas required for conveyor, steel, and walls is then:

$$\frac{48,800 + 193,300 + 70,000}{371.8} = 840 \text{ cu. ft. of gas per hour.}$$

The miscellaneous losses will be about 15 per cent because the small door and discharge chute are open all the time, and:

$$1.15 \times 840 = 970 \text{ cu. ft. of coal gas per hour, total gas consumption.}$$

Electric Furnace Calculations

The principles used in calculating current consumption for electric furnaces are similar to those for fuel-fired furnaces, but the units used are kilowatt-hours instead of B.t.u. The chief difference that distinguishes the electric furnace is the fact that there are no gases produced, which means no sensible heat losses from this source; also, the walls can be constructed of a small amount of firebrick inside and a large amount of insulation, because the temperatures never exceed 1850 deg. Fahr. with

metallic resistors and because there is no cutting action of flame impingement to destroy the firebrick lining.

The items considered above for fuel-fired furnaces are calculated in the same way as has been described, except that they must be converted to kilowatt-hours by dividing the values in B.t.u. by 3415. Since there is no heat lost by escaping gases, the efficiency of the electric current itself may be said to be 100 per cent, and the calculation is simplified. The following example of the calculation for a simple case is given to show the method:

Example 4, Batch-type Electric Furnace.

Construction.—Chamber 30 in. wide by $5\frac{1}{2}$ ft. long by 2 ft. high, inside dimensions. Sides, bottom, and roof are all constructed of $4\frac{1}{2}$ in. of firebrick and 10 in. of insulation.

Operation.—Six hundred and fifty pounds of parts are charged into the heated furnace and heated up to 1500 deg. Fahr. in $1\frac{1}{2}$ hours. They are then held at this temperature to soak for $\frac{1}{2}$ hour.

Calculation.—Heat to metal is $\dfrac{650 \text{ lb.} \times 240 \text{ B.t.u.}}{3415}$ 45.5 KW.

Heat to Walls:

	(Table 12)	(Table 13)	
	$2 \times 5\frac{1}{2}$ ft. $\times 2\frac{1}{2}$ ft. $\times 240/3415$	$\times$ 3	= 5.8
	2×2 ft. $\times 5\frac{1}{2}$ ft. $\times 240/3415$	$\times$ 3	= 4.6
	$2 \times 2\frac{1}{2}$ ft. $\times 2$ ft. $\times 240/3415$	$\times$ 3	= 2.2

Total heat to walls in 2-hour period is $2 \times 12.6 = 25.2$ KW.

Total heat to metal and walls 70.7 KW.

Plus 10 per cent for miscellaneous losses, current input required is 77 KW.

Actual measured current input for this furnace was 75 KW.

Practical Values for Fuel Consumption

The methods of calculation that have been outlined in this chapter are simplified methods of determining fuel consumption with sufficient accuracy for purposes of design, and the results obtained will closely approximate the quantity of fuel required

to do the work. There are some cases, as where a guarantee of fuel consumption must be made, where it is desirable to investigate further into the heat carried out by gases and absorbed by the walls, but these are the exceptions.

Since the results of these simplified calculations depend on certain assumptions, it is advisable to check them with any known measured results that can be obtained for a furnace of the same kind and size as that calculated. Table 15 gives practical values for average fuel consumption in furnaces of various types. These values should be used only for checking calculations or for very rough estimates, because the amounts of fuel in each case will vary considerably from the average given in the table, depending upon the rate of heating (pounds of material heated per square foot per hour), amount of insulation used on the walls, door construction, burner efficiency, and other lesser variables. The values given in the table are for the maximum rates of heating that are consistent with long furnace life and for the usual refractory construction in each case. They do not include any form of heat-saving appliance for conserving heat in the flue gases. The table also includes average furnace efficiencies, which are obtained by dividing the heat content in B.t.u. per pound absorbed by the metal, when heated to the final temperature given, by the B.t.u. per pound represented by the actual fuel burned. The values for maximum possible efficiencies without heat-saving appliances are the percentages of heat available in the fuel after the heat in the flue gases has been subtracted, i.e., inherent efficiency of the fuel itself at the temperature of the furnace. This value is 100 per cent for electric furnaces in all cases, as previously explained.

The figures given in Table 15 are principally for furnaces of large size, but fuel consumption in small portable furnaces should not be neglected. The importance of this class of furnaces is seldom realized, and the furnaces are usually of the crudest possible design and in the poorest state of repair. The reason for this is that each unit is comparatively small and turns out a satisfactory product as it is, so that almost every manufacturing plant continues to neglect a number of these home-made and

TABLE 15

AVERAGE PRACTICAL VALUES FOR FUEL CONSUMPTION

Furnace Type	Temperature, Deg. Fahr.	Fuel Required, B.t.u. per Pound of Metal Heated	Average Furnace Efficiency, Per Cent	Maximum Efficiency without Heat Saving, Per Cent
Fuel-fired:				
Drawing:				
Batch type	900	1050	10.5	80.5
Chain conveyor	900	1260		80.5
Hardening and tempering:				
Batch type	1500–1700	1400	17.2	62.8
Rotary hearth	1500–1700	1260	19.0	62.8
Pusher, direct	1500–1700	1350	17.8	62.8
Pusher, with pans	1500–1700	2100	11.4	62.8
Chain conveyor	1500–1700	1680	14.3	62.8
Annealing—car type	1650	980	25.0	61.5
Sheet annealing:				
Open annealing, roller hearth (hot material)	1500–1700	700	34.3	62.8
Box annealing	1500–1700	1120	21.4	62.8
Sheet furnaces		850	31.7	60.0
Pair furnaces		1120	24.1	60.0
Carburizing in boxes:				
Batch type	1650	3500	7.0	61.5
Pusher	1650	2150	11.4	61.5
Enameling:				
Continuous, sheets	1500–1650	1300	18.5	62.8
Batch, sanitary ware (three coats enamel)	1600–1800	600	40.0	60.0
Forging	2200	1820	18.7	54.0
Lead pots	1500	1500	15.3	65.5
Heating for forming:				
Batch	1900	1750	16.8	54.
Continuous	1900	1650	17.9	54.
Heating for rolling:				
Batch type	2400	2100	17.7	40.3
Continuous	2400	900	40.0	78.5

	Temperature, Deg. Fahr.	Metal Heated per KW.-Hr. Pounds	Furnace Efficiency
Electric:			
Annealing:			
Batch type	1650	5 – 6	36 –43
Car type	1650	6½– 8	47 –57½
Pusher, with pans	1650	8	½
Hardening and tempering:			
Batch type	1500	7 –10	46 –66
Roller hearth	1500	9 –12	59½–79
Pusher, direct	1500	9 –12	59½–79
Pusher, with pans	1500	7 –10	46 –66
Rotary hearth	1500	9 –12	59½–79
Carburizing in boxes:			
Batch type	1650	2 – 2½	½
Continuous	1650	2½– 3	18 –21½
Brass annealing, bright	1200	17–20	55 –65

disreputable orphans, with their leaning and bulging walls and with heat escaping from innumerable openings. Each one of these wrecks consumes only a small quantity of fuel, representing perhaps only $5 or less per day, which seems unimportant; but when the tremendous number of these furnaces is realized it becomes evident that a saving of 10 per cent in their fuel consumption would mean a saving of several millions of dollars annually in that extremely valuable commodity—fuel. Small furnaces of excellent design and construction can be bought at a price that is not so high as to smother their economy, so that the manufacturer can profitably contribute to conservation, if he will.

Table 16 gives typical fuel consumptions for small portable furnaces that are well constructed and have good burners but are not equipped with recuperators or automatic control of fuel.

Effect of Heating Rate.—It has already been stated that the fuel consumption varies with the rate of heating, as expressed by the pounds of material heated per square foot of hearth area per hour. This is true of all kinds of furnaces. The most efficient utilization of the fuel is obtained when the furnace is operated at the rate for which it is designed, and any considerable variation, either above or below this rate, will usually result in an increased amount of fuel required per pound of metal heated. If the amount of metal heated is low, the furnace temperature must be maintained at the same point as for normal rate of heating, which means that the heat lost to the walls per hour and the heat carried out by flue gases per unit of fuel are not reduced, so that the efficiency is lower. If, on the other hand, a high rate of heating is obtained by forcing the furnace, the proportion of losses is increased over those for normal operation. The heating time that the material is in the furnace is reduced, and this necessitates higher furnace temperatures with resulting higher hourly losses to walls and exhaust gases. Also, the velocity of the gases is increased, so that they leave the furnace before giving up as much heat, and the conditions for complete combustion of the fuel are usually not as good when a furnace is forced. Many furnaces do not show immediate

increase in fuel for higher than normal rate, but will if forced enough.

TABLE 16

AVERAGE FUEL CONSUMPTION IN SMALL FURNACES

Furnace Size, Inches	Fuel Required to Maintain Empty Furnace at Temperature		Fuel Required when Furnace is Operating at Maximum Capacity		Maximum Capacity Pounds of Steel Heated per Hour
	Gallons Oil per Hour, 140,000 B.t.u. per Gallon	Cubic Feet Gas per Hour, 560 B.t.u. per Cubic Foot	Gallons Oil per Hour	Cubic Feet Gas per Hour	
	Forging Furnaces—2200 deg. Fahr.				
24 × 18 × 18 high	2½	625	3½	870	250
36 × 36 × 24 high	6	1500	10	2500	700
48 × 54 × 30 high	10	2500	18	4500	1300
60 × 48 × 30 high	11	2750	20	5000	1400
60 × 60 × 30 high	14	3500	25	6250	1800
	Hardening Furnaces—1650 deg. Fahr.				
14 × 20 × 8 high	¾	190	1	250	80
20 × 40 × 15 high	2	500	3¼	800	250
	Annealing Furnaces—1400 deg. Fahr.				
36 × 45 × 18 high	2½	625	3½	870	320
36 × 72 × 18 high	3¾	925	5½	1380	550
48 × 50 × 18 high	3½	870	5½	1380	550
48 × 85 × 18 high	6¼	1560	9	2250	850
54 × 45 × 18 high	3¾	925	5½	1380	550
54 × 85 × 18 high	7	1750	10	2500	950
	Drawing Furnaces—900 deg. Fahr.				
36 × 45 × 18 high	1¾	440	2	550	300
48 × 50 × 18 high	2½	625	3	750	450
54 × 85 × 18 high	5¼	1320	6	1500	900

The following figures show the variation of fuel consumption with rate of heating for the car-type furnace, calculated in Example 2. It illustrates the effect of reduction in rate, but

does not show an increase in fuel for increased rate above normal. A car-type furnace of this kind can usually be made to heat more than the amount for which it is designed and with greater efficiency, but the product obtained is not so uniformly heated because of the dense piling required.

Tons Heated	Rate of Heating, Pounds per Square Foot per Hour	Gallons of Oil Burned per Ton	B.t.u. per Pound
4	8.3	23.2	1620
5	10.4	20.0	1400
6	12.5	17.8	1250
7	14.6	16.3	1140
8	16.7	15.1	1060
9	18.7	14.2	1000
Rated –10	20.8	13.4	940
11	22.9	12.9	902
12	25.0	12.4	870

The following figures show the variation for a large continuous billet-heating furnace designed for 20 tons of billets per hour at a low rate of heating, and fired by coke-oven gas having a heating value of 500 B.t.u. per cu. ft.

Tons Heated per Hour	Rate of Heating, Pounds per Square Foot per Hour	Gas per Ton, Cubic Feet	B.t.u. per Pound
10	10.4	3700	925
15	15.6	3400	850
Rated –20	20.8	3180	795
25	26.0	3020	755
30	31.2	2980	745
35	36.4	3030	757
40	41.6	3100	775
45	46.8	3170	792
50	52.0	3240	810

A variation above the normal rate is slower to affect the fuel consumption than is a reduction in the rate of heating. Increased fuel consumption is the only serious objection to low rates of heating in a furnace too big for its production, but for excessive rates of heating it is an objection of less importance than those of injury to the furnace brickwork and improper heating of the product.

Heat-saving Methods

Methods of heat saving include special furnace arrangements, recuperators and regenerators, waste-heat boilers, insulation of refractories, attention to burner efficiency, good mechanical construction and selection of refractories, and automatic control of temperature and combustion.

Special furnace arrangements include preheating chambers, compensating furnaces, and continuous furnaces in general. The first arrangement is common in connection with small heat-treating furnaces and salt or lead baths. Its primary purpose is usually to preheat the material to prevent cracking from sudden exposure to high temperatures, but fuel economy also results because the preheating chamber is heated by waste gases from the high-heat chamber. Compensating furnaces are those in which the material is preheated by radiation from material which has been heated and is cooling, and there are various arrangements. One type is the batch car-type furnace to which is attached an insulated chamber large enough to hold two cars, one that has been heated and one that is waiting to enter the heating furnace. The cooling car of material gives up its heat to the waiting car and results in a fuel saving. The efficiency of this saving device depends to some extent on the time cycle between car transfers because, after the temperatures of the two cars have become equal, the resulting temperature will gradually drop in spite of excellent insulation of the chamber. The ideal time for transfer is when the temperature has reached equilibrium, and any delay beyond this point reduces the saving. With a 1600-deg. Fahr. furnace and cars containing about 5 tons

of material, the temperature reaches its maximum in about four hours, so that with the usual eight-hour cycle in the case of annealing castings, the temperature drops from this high point to about 400 deg. Fahr. effective preheat. Another form of compensating furnace is the counterflow arrangement of continuous furnace. The furnace length is divided into three zones —preheating, heating, and cooling—and two rows of material pass through the furnace in opposite directions. The cooling of one row then preheats the material in the other row at one end, and *vice versa* at the other end.

The ordinary continuous furnace is efficient because of the counterflow between material and hot gases, as distinguished from counterflow of two rows of material in the compensating type. As the gases flow from one end of the furnace, they give up their heat to the cold material and leave the furnace at low temperatures and with very little sensible heat. Such a furnace is usually 40 to 60 per cent efficient.[3] It should be mentioned that all continuous furnaces are not efficient, because many of them are heated by burners located along their full length, and the charging temperature is maintained about the same as at the discharge end. These furnaces are used for their labor-saving advantages and are heated their full length to reduce the furnace length required. They are not much more efficient than a corresponding batch-type furnace, because the flue gases leave at the same temperature as that of the furnace in both cases. A continuous furnace of any type is usually somewhat more efficient than the batch type, owing to elimination of wasted time in charging and discharging.

The principle of recuperators and regenerators is to extract some of the heat from the waste gases after they have left the furnace and return this heat to the furnace in the form of sensible heat in the combustion air. Regenerators usually consist of two chambers containing a checker work of bricks. The flue gases and combustion air are alternately passed through these

[3] See *Industrial Furnaces*, Vol. I, by W. Trinks, for theory of continuous furnaces.

chambers by reversing the directions of the flow of fuel through the furnace, and the brick alternately absorbs heat from the hot gases and gives it to the cold air for combustion. As brick checkers are costly and rather awkward in application to most heating furnaces, they are not extensively used, but forms of portable metal regenerators have been developed to compete with the more flexible recuperators. A recuperator is an apparatus for continuously transferring heat from flue gases to combustion air. The hot gas and cold air flow in many streams through adjacent passages, which are separated by walls of material having good thermal conductivity. They are made of metal or tile, and designed so as to give the greatest possible conduction of heat with the minimum leakage and deterioration.

The amount of air preheat which can be obtained depends on many variables, which include the size of the recuperator or regenerator, the temperature of the flue gases entering the apparatus, and the rate of heating of material in the furnace, all in addition to the actual design of the appliance. Detailed methods of calculation for the design of recuperators and regenerators are available in various books and manufacturers' publications.

A large number of heat-saving appliances that are installed are not economical because the saving obtained does not offset the first cost and the cost of upkeep necessary on the appliance. A recuperator for any purpose must have considerable area, and the smallest sizes are fairly costly. The result is that there are many furnaces which use such a small amount of fuel that the saving possible with a recuperator is not enough to pay for the cost of the smallest size in a reasonable length of time. Also, in many cases, the furnace is already very efficient, and the temperature of the flue gases is so low when they enter the recuperator that an economical air preheat cannot be obtained. Some idea of the relation between preheat and saving can be obtained from the following figures, calculated for 1600 deg. Fahr. gases entering a recuperator from the combustion of fuel oil with 10 per cent excess air.

Air Preheat, Deg. Fahr.	Fuel Saving, Per Cent of Fuel Consumption
200	4.3
300	7.1
400	10.8
500	12.3
600	14.8
700	17.0
800	19.2

The method of figuring these values follows:

Heat in oil (lower heating value—Table 2) = 140,000 B.t.u. per gal.

Heat in flue gases (10 per cent excess air) at 1600 deg. Fahr. (1505 + 10 per cent $\times$ 1410) $\times$ 0.076 $\times$ 0.25 specific heat $\times$ (1600 − 60) = 48,100

Heat left in the furnace = 91,900

Preheat in air at 300 deg. Fahr. (1410 + 10 per cent $\times$ 1410) $\times$ 0.076 $\times$ 0.25 $\times$ (300 − 60) = 7,060 B.t.u. per gal.

Per cent saving: $\dfrac{7{,}060}{91{,}900 + 7{,}060} \times 100 = 7.13$ per cent.

In considering the installation of a heat-saving appliance, the degree of preheat that can surely be obtained with the proposed appliance must first be determined for the conditions to be met (rate of heating, flue-gas temperature, etc.). The amount of fuel saving corresponding to this preheat for the conditions should then be enough to pay for the cost and upkeep of the apparatus in a reasonable time. Also, the life of the apparatus must be guaranteed to be of such a length that there will be sufficient time left after it has paid for itself to allow some profit on

the investment. There are usually advantages, such as decreased oxidation of work, which can be credited to recuperators, but as it is difficult to forecast the financial saving from these advantages it is questionable whether the investment should be justified to any extent on them.

Many successful waste-heat boiler applications have been made on industrial furnaces of comparatively low temperature, and the use of boilers will probably grow as fuel costs increase. The principle of waste-heat boilers differs from other economy apparatus for furnaces in that the heat extracted from the flue gases may be used for a purpose entirely independent of the furnace instead of being returned in some form to the furnace. The power developed is therefore classed under useful heat in a heat balance of the furnace, as explained at the beginning of this chapter.

The boiler horsepower which can be developed in waste-heat boilers is expressed by the following formula:

Boiler horsepower

$$= \frac{\text{heat in flue gases entering boiler}}{34.4 \text{ lb. water/B.HP.} \times 970 \text{ B.t.u. lb.}} \times \text{boiler efficiency.}$$

The horsepower developed by the products of combustion of 100 gal. of fuel oil (10 per cent excess air) with 1600 deg. Fahr., leaving temperature and 50 per cent boiler efficiency is:

$$\frac{\begin{array}{c}100 \text{ gal.} \times (1505 + 1410 \times 0.10) \\ \times\, 0.076 \text{ lb./cu. ft.} \times 0.25 \times (1600 - 60)\end{array}}{34.4 \times 970}$$

$$\frac{4{,}810{,}000 \text{ B.t.u.}}{34.4 \times 970} \times 0.50 = 72.0 \text{ B.HP.}$$

The relation between the boiler horsepower developed and the heating surface required in waste-heat boilers depends on the temperature of the gases entering the boiler and is indicated by the following:

Entering Gas Temperature, Deg. Fahr.	Square Feet per B.HP.
1700	12.0
1500	13.3
1300	15.1
1100	18.0
900	23.5

These figures are approximate, but will serve for a preliminary estimate of the size of boiler required in any case.

With increasing costs of fuel, the use of waste-heat boilers will be considered more seriously and will become more common. This is indicated by the large number of waste-heat boilers to be found in European countries.

The use of insulation as a means of fuel conservation will be fully discussed in the next chapter, and the automatic control of combustion will be covered in Chapter VIII. Insulation increases efficiency by reduction of radiation, while automatic control prevents excessive pressures and temperatures or excessive variation from good fuel and air proportions in combustion.

Good furnace construction, resulting in a furnace that has a minimum of leakage, is an excellent method of fuel saving, particularly with small furnaces. Leakage through doors is an example of avoidable heat losses. All doors should fit tightly against the furnace and should drop into some form of wedge to hold them tightly against the furnace when closed. Such refinements will save a great deal of heat in a year and cost practically nothing, but they are seldom found because they are not likely to be included when a brick box is simply thrown together without any thought. If all of the unnecessary leakage to be found in industrial furnaces could be eliminated, the total yearly saving for the many thousands of furnaces in operation would unquestionably be enormous.

With the completion of this general consideration of fuel consumption, we come now to the mechanical construction of the furnace, which will be discussed in the two chapters that follow.

CHAPTER VI

REFRACTORY DESIGN AND CONSTRUCTION

Before taking up the detailed design of industrial furnaces it is desirable to review briefly the preceding chapters in order to recall to mind the preliminary studies that must be made before it is possible to proceed with the actual design. In Chapter II the various furnace fuels were discussed, together with the factors to be considered in the selection of the fuel best suited for the conditions to be met. The selection of the fuel led to the application of the fuel to the furnace; and the various locations of combustion chambers, with respect to the heating chamber, to secure the best utilization of the heat in the fuel under different conditions, were discussed in Chapter VIII. As many of the items involved in this question are also met in the method of handling the heating material through the furnace, Chapter IV completed the discussion of these questions. Finally, Chapter V discussed the calculation of fuel consumption to be expected in the furnace.

At this point, then, we are ready to consider the design of the furnace details, and may assume that the fuel, general furnace arrangement, method of material handling, and heating-chamber dimensions have been decided upon, and that the probable fuel consumption has been estimated. This chapter will consider the details of refractory construction and foundation design as definitely as is possible in a general discussion which must consider all kinds of furnaces. The chapter can be conveniently divided into four principal discussions: dimensional layout of refractory lining, properties and selection of refractory materials of construction, mechanical construction, and foundations. The first step is to lay out the refractory portions of the furnace on paper in order to determine and record the various dimensions.

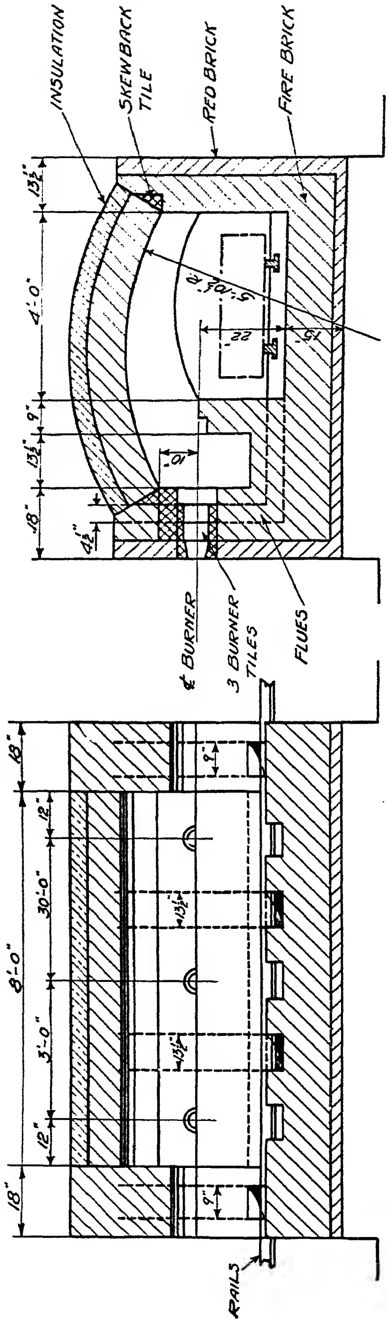


FIG. 55.—Typical Lay-out of Furnace Refractories.

Dimensional Layout of Furnace Refractories

As an example, suppose that a sidefired, oil-burning, pusher-type furnace is to be designed for heating boxes 36 in. long by 18 in. wide by 12 in. high, outside dimensions. A cross-sectional view and a longitudinal section are necessary to show the refractory construction of a furnace, and in some cases a plan view is required. Figure 55 illustrates the completed views necessary to show all details of brickwork arrangement. It is usually easiest to make the cross-sectional view first, because the proper furnace height can best be found in the construction of this view and because the crown height of the arch is determined mechanically by laying out the arch with a compass. The steps in the completion of these views may be divided for discussion into the following items: interior dimensions, location of burners and flues, size of flues and stacks, brick thicknesses, and insulation.

Interior Dimensions.—The inside length and width of the heating chamber of Fig. 55 are assumed to have already been determined at 4 ft. and 8 ft., respectively, by the methods of Chapter III, and the next step is the determination of the height. This dimension depends to some extent upon the height of the heating material, and must be great enough in fuel-fired furnaces to prevent any flame from striking the work directly and to allow ample space above the material for circulation of gases; but it must not be so great that it will be difficult to heat the furnace uniformly. In sidefired furnaces, the height of the bridgewall is the important height, and is equivalent to the height of the burner centerline in direct firing. In all other types the height may be considered to the skew of the arch. In most cases, these heights are somewhere near one-third of the heating-chamber width when the heating material is very shallow on the hearth, and about 6 in. to 12 in. above the top of higher charges. In the case of the example, the bridgewall is 6 in. above the charge and the height is 22 in. With the burner centerline at the top of the bridgewall, and allowing 5 in. to the top of the burner tile and 5 in. for the thickness of the tile spanning the burner opening, the skew height is 32 in., or 2 ft. 8 in., above the hearth. If the estimated fuel consumption of this furnace has been found to be 12 gal. of oil per hour and there are three burners, each burner will burn about 4 gal. of oil per hour, and 13½ in. is sufficient for the combustion-chamber width, as explained in Chapter III. A thickness of 9 in. for the bridgewall is necessary for satisfactory life and strength, and the total width of the furnace inside is, therefore, 5 ft. 10½ in. Furnace arches are usually made with the radius equal to the span, and with this arrangement the rise of the arch is 0.134 times the span, or in this case 14½ in. to the nearest fraction. This design gives a skew angle of 60 deg. against which the arch rests, and affords a maximum of strength to the arch construction. Further consideration of the height of furnace heating chambers will be given in one of the problems of Chapter IX, where the height of a furnace will be analyzed for a special set of conditions. Data of assistance in the determination of combustion-chamber sizes were given in Chapter III.

Location of Burners and Flues.—The vertical location of burners depends upon the method of firing. In general, they are located at the bottom of underfired combustion chambers, at the top of overfired chambers, on a level with the top of the solid bridgewall in sidefired chambers (see page 60), and high enough in direct-fired furnaces to prevent any flame from directly striking the material. Their location along the length of the furnace determines the heat distribution. The lowest capacity at which most oil burners will operate satisfactorily is about 2 gal. per hour, and for that reason they are seldom located closer than 2 ft. apart. The maximum distance is about 4 ft., and the usual separation about 3 ft. for good heat distribution. These dimensions apply whether the burners are all on one side of the furnace or staggered alternately along the opposite sides. Gas burners can be designed for smaller equivalent amounts, and the average spacing is about 2 ft. with a correspondingly greater number of burners. In the example, for the length of 8 ft., three oil burners 3 ft. apart with 1 ft. left at each end is a good arrangement. Burners should always be near the doors, where the greatest amount of heat is needed.

The general location of flues for the different firing arrangements was discussed in Chapter III. The specific location along the furnace length is usually directly between burners and with the end flues as near the door as possible, to short-circuit any cold air which may enter the door. Flues in the sidewalls are connected to the furnace interior as near the hearth level as possible, to make it easier to keep the bottom of the furnace hot and to control the temperature distribution. The depth of the sidewall flues is always a brick dimension, usually $4\frac{1}{2}$ in. as in Fig. 55, and they are located in the second brick course from the furnace side of the wall and constructed by omitting bricks in this course. Most heating-furnace flues vent the furnace gases directly into the atmosphere at the top of the wall in which they are located. Flues are also frequently located in furnace arches. Too many flues are better than too few, because they are difficult to build after the brickwork is completed and any excess flues can be covered over in operation. Flues in a wall

should be at least 9 in. apart to prevent excessive weakening of the wall.

Where a stack is used with the furnace, the flues generally extend downward into the foundation of the furnace, where they connect with horizontal, brick-lined flues which extend underground to the stack base. The question of the use of stacks with heating furnaces is an interesting one, and it is appropriate to discuss it at this point. The use of stacks with many types of steel-mill furnaces is an old-fashioned practice that has become traditional through long and honorable use, but in many cases very much better results would be obtained if they were eliminated, especially with oil- and gas-fired furnaces. The problem on this subject in Chapter IX best illustrates this argument. This problem clearly shows that much greater vacuums and pressures result from fuel variation in a furnace with a stack, which means that when a stack is used large quantities of cold air rush into the furnace when the fuel is reduced, and when the furnace is forced, a cutting flame is forced out through every opening. All this could be reduced by intelligent control of the damper, but the practical fact is that this damper is frequently rusted into position. The only advantage of a stack is that it removes fumes, and with gas and oil fuels this can better be done by proper ventilation of the furnace room than by an appendage which magnifies pressure variation and wastes fuel. A stack is, of course, necessary on a furnace fired by coal with natural draft, to draw air through the fuel on the grate, and this was no doubt the origin of its traditional use. A stack is also required for long, continuous furnaces, to draw the combustion gases through the furnace; and for furnaces equipped with recuperators or regenerators, to produce circulation of gases through these units.

Size of Flues and Ports.—This subject is treated in detail in Vol. I of *Industrial Furnaces*, by Professor Trinks, and only the general rule will be given here. The resistance of the flues and ports to the passage of waste gases minus the draft in the flues equals the furnace pressure, and for proper design the furnace pressure corresponding to the average amount of fuel should equal about

0.01 in. water pressure. The detailed calculation of flue dimensions to accomplish this is a complicated physical problem involving the theory of the flow of gases, but a quick practical determination may be obtained from Table 17, which gives the allowable velocities in feet per second for gases from furnaces operated at different temperatures.

TABLE 17

ALLOWABLE VELOCITIES IN FLUES, FEET PER SECOND

Flue Size, Inches	Furnace Temperature, Deg. Fahr.			
	200	1000	1500	2000
$4\frac{1}{2} \times 4\frac{1}{2}$	7.5	10.0	11.0	12.0
$4\frac{1}{2} \times 9$	8.3	12.3	13.8	15.3
9×9	10.2	13.2	14.5	16.2
$9 \times 13\frac{1}{2}$	11.7	16.4	18.8	21.6
$13\frac{1}{2} \times 13\frac{1}{2}$	13.2	18.2	22.0	24.5

If the approximate fuel consumption has been calculated and the quantity of flue gases obtained as described in Chapter V, the theoretical flue area required can be determined by using the velocities in this table. The flue area obtained will be somewhat larger than is actually necessary, but it is better to have it so, because it is easier to adjust a flue that is too large than it is to make a small one larger. A flue that is too large is usually partially closed off by means of a brick laid over the outlet.

In the example of Fig. 55, the fuel consumption was given as 12 gal. of oil per hour, and each gallon will produce about 1650 cu. ft. of flue gases (cold measure, including 10 per cent excess air), and:

$$1650 \times \frac{1600 + 460}{62 + 460} \qquad \text{cu. ft. at 1600 deg. Fahr.}$$

The total gases per second then equal:

$$\begin{matrix} 1. \times \\ 3600 \text{ sec./hour} \end{matrix} = 21.7 \text{ cu. ft.}$$

The flues in this furnace must be $4\frac{1}{2}$ in. deep to keep the furnace wall down to a reasonable thickness, so they will probably be $4\frac{1}{2} \times 9$ in. flues. Consulting the above table, a velocity of 15 ft. per sec. appears to be a safe average figure to use in this case. The required area is then:

$$\frac{21.7 \text{ cu. ft./sec.} \times 144}{15 \text{ ft./sec.}} = 208 \text{ sq. in.}$$

Four flues, two $13\frac{1}{2}$ in. each between burners, and one 9 in. at each end, and all of them $4\frac{1}{2}$ in. deep, will make a total area of 203 sq. in., which is about right.

When the gases escape through ports in the roof of the furnace, somewhat higher velocities are allowable, because a short port does not offer so much resistance as a longer flue of the same area, but, as stated before, it is desirable that the flues or ports be too big rather than too small. It is difficult to set up general rules for the determination of flue sizes for all conditons, but the foregoing figures will serve as a safe guide in that determination.

For quick estimates of flue areas required, Table 18, which gives the square inches of flue area required per unit of different fuels, may be used. As an example, a 2000-deg. Fahr. furnace burning 1000 cu. ft. of natural gas per hour should have a total flue area somewhere near:

$$1000 \times 0.15 = 150 \text{ sq. in.}$$

Firebrick Thickness.—The discussion of firebrick thickness may be divided into four parts: arches, walls, hearths, and miscellaneous. The thickness of furnace arches depends upon the span, and the usual practice is to use a $4\frac{1}{2}$-in. arch for spans less than 3 ft., 9 in. between 3 ft. and 10 ft., and $13\frac{1}{2}$ ft. up to 16 ft., which is about the upper limit for spans of any thickness. The

above practice is not absolute, because it depends somewhat upon the temperature. For very low temperatures, 4½-in. arches are made as wide as 8 feet, and 9-in. arches up to 14 ft. in span. The limits are also somewhat broader in electric furnaces, where the temperature never exceeds 1900 deg. Fahr. and where there is no cutting action of flame.

TABLE 18

FLUE AREAS FOR DIFFERENT FUELS

Fuel	Temperature of Leaving Gases, Deg. Fahr.	Required Flue Area, Square Inches per Unit of Fuel Burned per Hour
Bituminous coal, pounds	1000	1.47
	2000	2.01
Fuel oil, gallons	1000	14.2
	2000	19.4
Natural gas, cubic feet	1000	0.11
	2000	0.15
Coke-oven gas, cubic foct	1000	0.045
	2000	0.062
Coal gas, cubic feet	1000	0.058
	2000	0.079
Raw producer gas, cubic feet	1000	0.017
	2000	0.023

The thickness of firebrick used in the construction of walls is dependent upon mechanical strength, furnace temperature, flue construction, and general nature of the furnace. Very small furnaces for heat treating and pot furnaces are usually built with 4½-in. walls, as are larger electric furnaces and fuel-fired furnaces for low temperatures. Fuel-fired furnaces of any size for temperatures above 1000 deg. Fahr. are seldom built with less than 9 in. of firebrick, and when the temperature reaches 2000 deg., 18 in. of firebrick should be used (or 13½-in. firebrick and 4½-in. red brick). Firebrick, on account of its soft texture, is seldom

used for the outside of furnace walls, either red brick or insulation and a steel or cast-iron casing being employed. Red-brick facing is seldom over 4½ in. thick, and while it has the same insulating properties as firebrick, it must be well protected from the heat by firebrick to prevent cracking. Insulation must also be well protected, as most of it will shrink or crumble if subjected to too high a temperature.

Where flues pass through the sidewalls, the walls must be of at least 13½ in. of firebrick, because the flue cannot be bounded by either red brick or insulation on account of the temperatures of the flue gases. The endwalls of furnaces are much the same as the sidewalls, except those which contain large doors. In this case, the entire space surrounding the door is covered with cast iron, and the entire wall is built of firebrick with no red brick. Door walls are usually 13½ in. if the door is 5 ft. wide or more, to insure a stable and lasting door arch. The above thicknesses of firebrick are not changed by the addition of insulation, because firebrick thickness is determined by strength requirements to a greater extent than by insulating value, and the addition of insulation does not add much to the strength of a wall.

The amount of firebrick in furnace hearths depends upon the width of the furnace and the temperature. Hearth thicknesses are usually about one-eighth of the furnace width (center to center of sidewalls) for temperatures of about 1800 deg. Fahr. and one-sixth of the same dimension for temperatures of about 2200 deg. Fahr. In any furnace, hearths should be at least 10 in. thick for temperatures up to 1200 deg. Fahr., 12½ in. to 1500 deg., 15 in. to 1800 deg., and 20 in. above 1800 deg. In the last two cases, the bottom course can be made of red brick. For portable furnaces, where the bottom is supported by structural steel, the thickness does not have to be so great, because the bottom is to some extent cooled by circulation of air underneath the furnace.

The miscellaneous firebrick parts of a furnace include door linings, piers, bridgewalls, and underfired hearths. Firebrick door linings are used only on very high-temperature furnaces, and are usually 7 in. thick, made up of a rowlock (bricks on

edge) course and a flat course. No general rules will apply to these items. They must be made heavy enough to withstand the stresses to which they will be subjected at the maximum temperature to which they will be heated, and their design must be learned from experience.

Insulation.—Having laid out the arrangement of firebrick in the furnace, the next step, before the method of holding the furnace together can be considered, is to determine the amount of insulation to be used. The use of insulation is rightly increasing in popularity, but like all good things it can be, and frequently is, overdone to such an extent that all the benefits are lost and its use becomes an expense rather than a saving. Each case is a separate problem and the determination of the economical amount of insulation is complicated by several variables; but let us see whether, with a little care, the proper amount of insulation can be intelligently determined.[1]

All calculations must be based on the actual heat losses through walls, and Table 12 (reproduced from Chapter V for convenient reference) shows practical values for the heat losses through walls made up of common thicknesses of firebrick and insulation for different furnace temperatures, expressed in B.t.u. per square foot of inside furnace area per hour.

From Table 12, the difference between the heat lost with plain and insulated firebrick of various thicknesses can be calculated, this difference representing the saving in heat lost through the wall by the use of insulation. Then for each B.t.u. saved in radiation there will be a corresponding fuel saving, the relation between these two figures depending upon the thermal efficiency of the furnace. This term is used to designate the relation between the value, heat in fuel minus heat in the flue gases, and the heat in the fuel burned. The variation of the thermal efficiency with the temperature and the fuel used is shown in Table 19, which was calculated on the basis of average values of 10 per cent excess air for fuel oil; 20 per cent for coal, stoker-fired; and 10 per cent for artificial gas.

[1] The following analysis is from an article by the author, published in *Forging-Stamping-Heat-Treating*, September, 1926.

TABLE 12 (Repeated from Chapter V)

HEAT LOSSES THROUGH VARIOUS FURNACE WALLS, B.T.U. PER SQUARE FOOT PER HOUR

Firebrick, Inches	Insulation, Inches	Furnace Temperature, Deg. Fahr.						
		1000	1200	1400	1600	1800	2000	2200
4½	0	1050	1250	1480	1860	2130		
	2½	450	510	600	720	850	1005	
	5	216	300	375	450	530	610	
	7½	178	215	265	315	362	410	
	10	150	185	220	260	295	330	
	12½	140	165	190	220	250	280	
9	0	550	700	860	1040	1220	1400	1600
	2½	310	380	460	560	660	762	865
	5	204	244	269	339	364	429	490
	7½	170	200	232	266	300	334	370
	10	140	170	199	226	253	281	310
	12½	125	150	170	190	212	235	260
13½	0	405	500	590	700	830	975	1120
	2½	230	300	380	455	535	615	705
	5	166	204	244	259	314	349	396
	7½	150	175	200	226	255	285	320
	10	128	150	176	200	228	254	280
18	0	264	365	460	560	660	760	865
	2½	180	239	267	319	367	455	515
	5	149	181	215	247	280	311	349
	10	127	148	170	194	220	240	270

It is at once apparent that when savings from Table 12 are divided by the efficiencies of Table 19 to obtain the saving at the burner or grate, the effect of variation of temperature and fuel on the fuel saving at the burner or grate will be very marked. It is therefore necessary that the saving in heat lost through the

walls be corrected for this variable efficiency before a cost analysis can be obtained.

TABLE 19

FURNACE THERMAL EFFICIENCY—PER CENT VARIATION WITH TEMPERATURE AND FUEL

Temperature, Deg. Fahr.	Oil	Coal, Stoker-fired	Artificial Gas	Electricity
1000	78	76	77	100
1200	73	72	72	100
1400	68	66	67	100
1600	63	66	62	100
1800	57	55	56	100
2000	52	48	51	100
2200	46	42	45	100

Having determined the true saving in actual fuel consumption, we obtain the financial saving by multiplying by the cost of the fuel. For comparison, the cost of atomized oil was figured at 7.2 cents per gal. of 144,000 B.t.u., stoker-fired coal at $5.40 per ton with a heat value of 12,400 B.t.u. per lb., artificial gas at 61.5 cents per 1000 cu. ft. of 560 B.t.u. cu. ft., and electricity at 1.5 cents per KW-hr.

The cost of insulation per square foot, including insulating brick, steel plates necessary, and labor, was figured to be 64 cents for $2\frac{1}{2}$ in. of insulation, $1.03 for 5 in., $1.42 for $7\frac{1}{2}$ in., $1.81 for 10 in., and $2.20 for $12\frac{1}{2}$ in.

Assuming that it is desired that the insulation pay for itself in a certain period consisting of a definite number of working hours, the saving in fuel per hour can be multiplied by this number of hours as a basis for comparison. The difference between the cost of insulation and the saving in this period is the net saving or loss at the end of this period.

As an example of the above method of calculation, the following are the comparative figures for the net saving with different

fuels and 5 in. of insulation applied to 9 in. of firebrick at 1600 deg. Fahr. furnace temperature, on the basis of six months' time of 1500 working hours.

	Oil	Coal	Artificial Gas	Electricity
Heat loss, 9 in. firebrick	1040	1040	1040	1040
Heat loss with 5-in. insulation	339	339	339	339
Saving, B.t.u. per square foot per hour	701	701	701	701
Thermal efficiency, per cent	63	60	62	100
Saving, fuel, B.t.u. per hour	1110	1170	1130	701
Saving, dollars in 1500 hours	0.83	0.38	1.86	4.62
Cost of insulation, dollars	1.03	1.03	1.03	1.03
Saving or loss, dollars in 1500 hours per square foot	$0.20 Loss	$0.65 Loss	$0.83 Profit	$3.59 Profit

The accompanying curves, Figs. 56 to 66, show the relations between cost of insulation and saving in 1500 hours for various combinations of firebrick and insulation and for various fuels and temperatures, all calculated by the above method. These curves apply only for the assumptions as previously outlined, but, since the calculations involve only simple relations, it is easy to revise the curves for either saving or cost on the vertical scale to correspond to any change in fuel cost, desired rate of amortization, or difference in cost of insulation from that which has been used. The intersection of the saving and cost lines for the same amount of insulation gives the temperature at which the insulation will pay for itself in 1500 hours with the values as selected.

It will be seen from a study of these curves that, up to a certain amount, insulation effects a very considerable saving, but that above this amount the saving per inch of additional insulation becomes gradually smaller. The actual saving or loss for any condition of temperature, fuel, or brick thickness can be obtained by comparing the values of insulation cost and saving given on these curves.

The first step in the selection of insulation is a determination of the time limit that is to be allowed for the insulation to pay for itself. Since the saving from insulation after it has paid

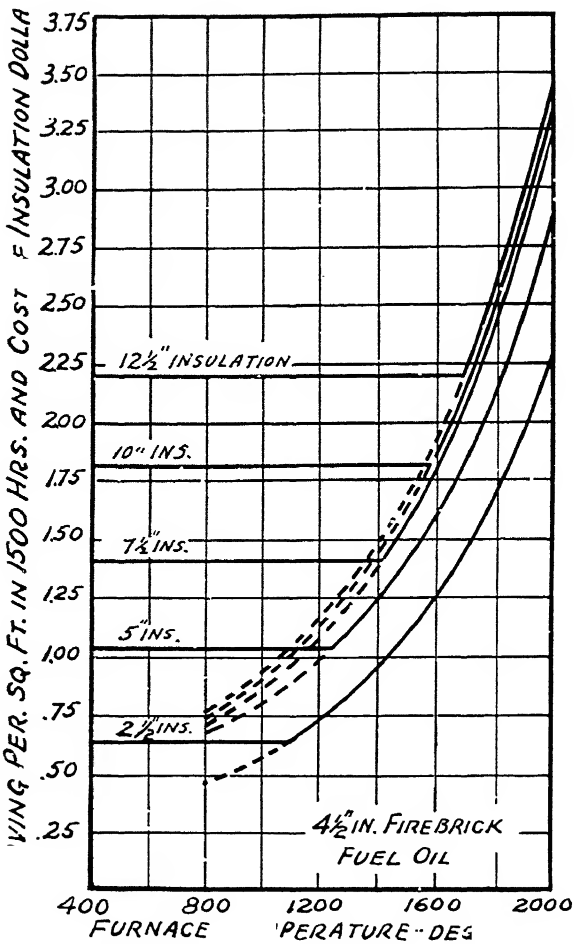


FIG. 56.—Economy from Insulation Applied to 4½-in. Firebrick with Fuel Oil.

for itself is clear profit, and because the usual life of furnace and insulation is about five years, almost any reasonable amount of insulation will show a profit before the furnace is worn out;

but most companies adhere to a definite policy of time allowance in which equipment must pay for itself, regardless of probable life. This definite time is selected because of the rapid changes

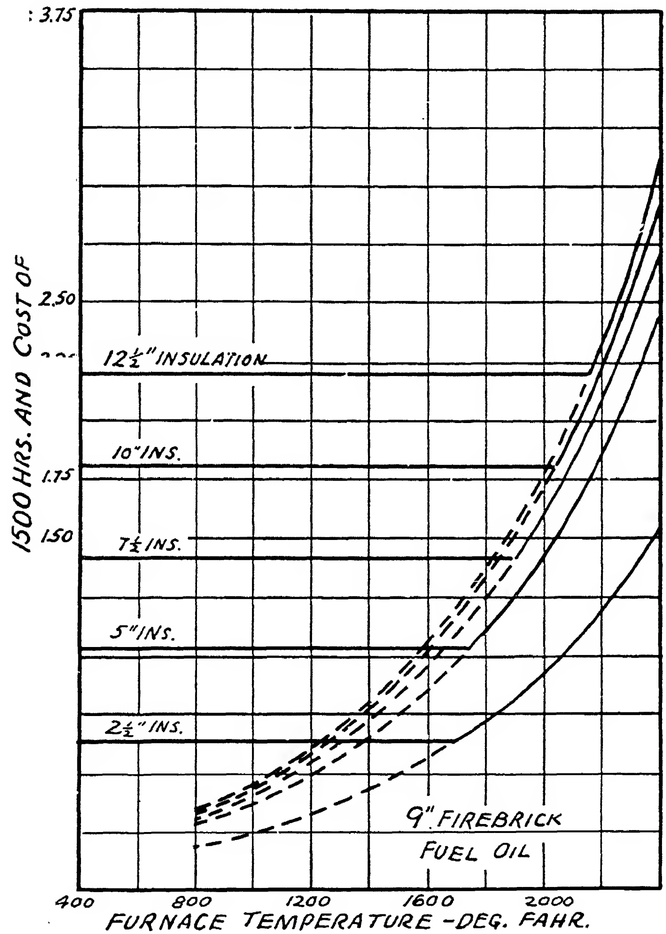


FIG. 57.—Economy from Insulation Applied to 9-in. Firebrick—Fuel Oil

in equipment and methods, and the consequent possibility that some change will be made before a satisfactory profit has been realized if the time allowance is too great. This allowance

varies from six months to two years, depending on the nature of the operation involved and the financial policy of the company.

After this time limit has been determined, if it is greater than

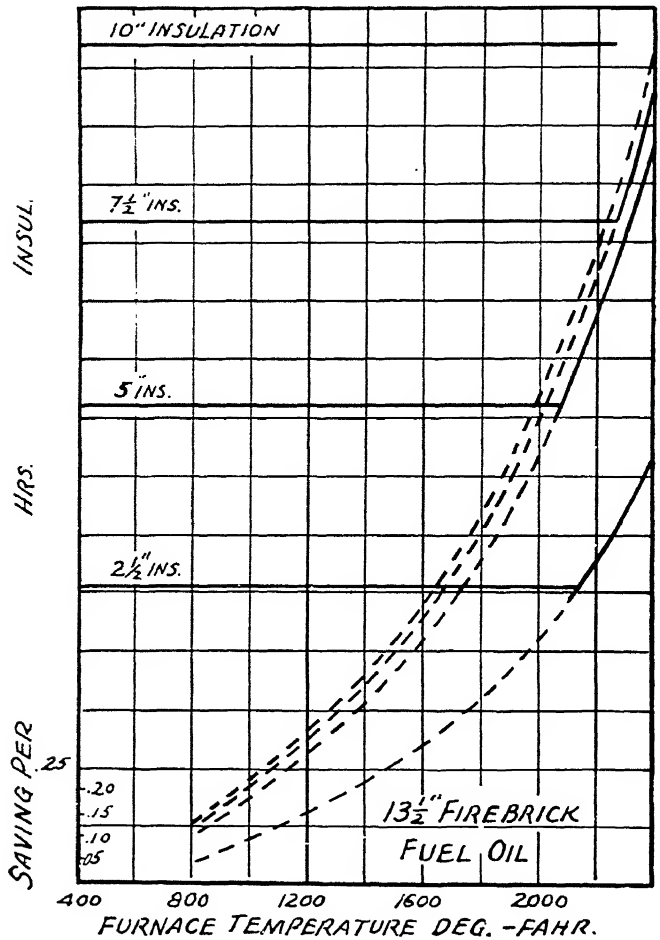


FIG. 58.—Economy from Insulation Applied to 13½-in. Firebrick—Fuel Oil.

six months, as used in the curves, they can be revised by increasing the saving in proportion to the increase in the number of hours allowed over the 1500 hours figured. The saving or loss in money for any case can then be calculated as outlined above.

Where it is not necessary to know the actual saving, but simply to determine the correct quantity of insulation to use, Table 20 can be used if the original assumptions of cost of insulation

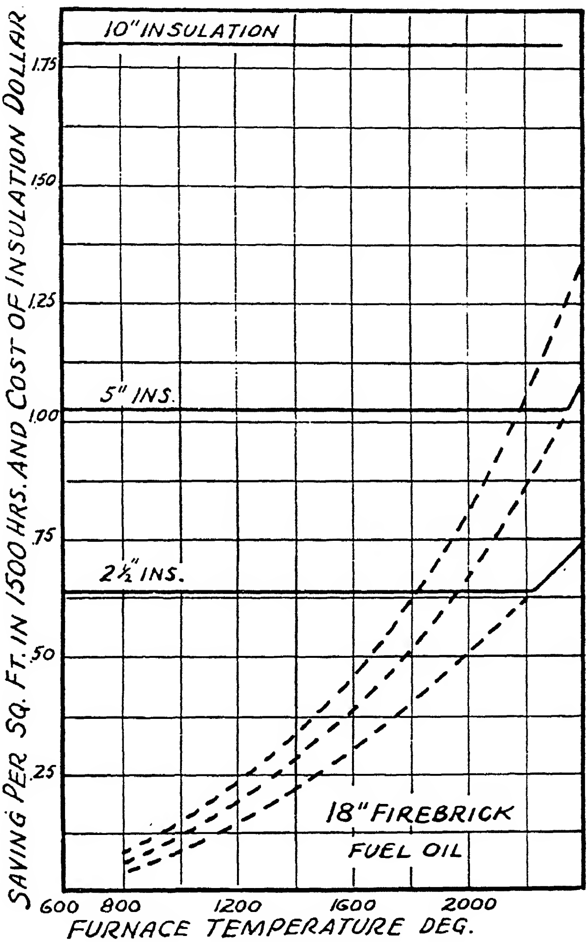


Fig. 59.—Economy from Insulation Applied to 18-in. Firebrick—Fuel Oil.

and fuel apply. This table shows for all cases the number of months which are required for insulation to pay for itself, and if the time allowance for amortization is known, the correct amount of insulation can be selected directly from the table for

any condition of temperature, fuel, and brick thickness. The lines given in the table mark the desirable amounts of insulation for a time allowance of six months of 1500 hours.

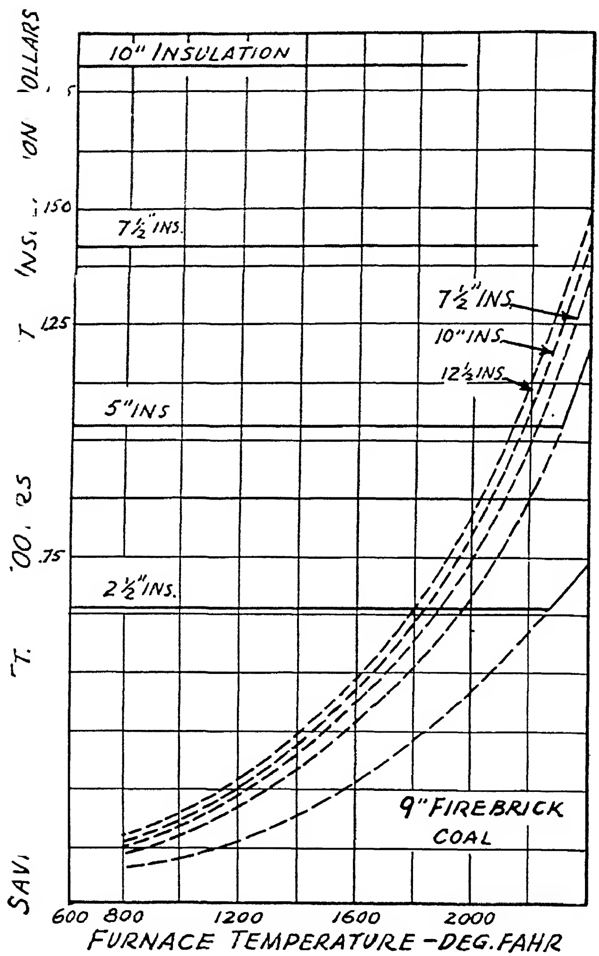


Fig. 60.—Economy from Insulation Applied to 9-in. Firebrick—Coal.

As an example of the use of these tables in selecting the proper amount of insulation, suppose that it is desired to find the proper amount of insulation for an oil-fired furnace operating

at 1600 deg. Fahr. and having 9-in. firebrick walls. If the rule of the company, or circumstances, make it desirable that the insulation pay for itself in six months of 1500 working hours,

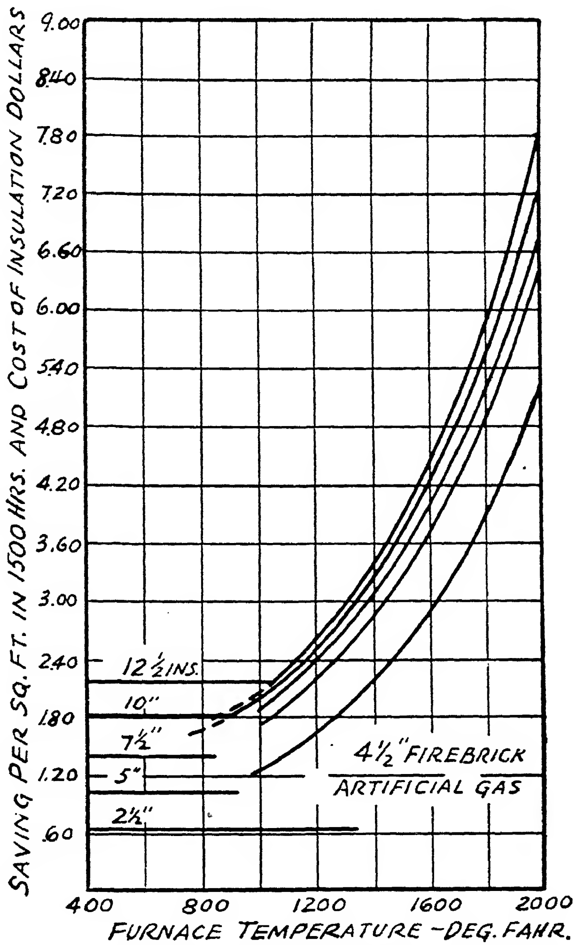


Fig. 61.—Economy from Insulation Applied to 4½-in. Firebrick—Artificial Gas.

reference to the table shows that less than 2½ in. of insulation should be used; but if seven or eight months is satisfactory, 5 in. can be used; and even 12½ in. will pay for itself in one year in this case.

In conclusion, it is apparent from a study of the charts and curves that each case should be considered as a separate problem,

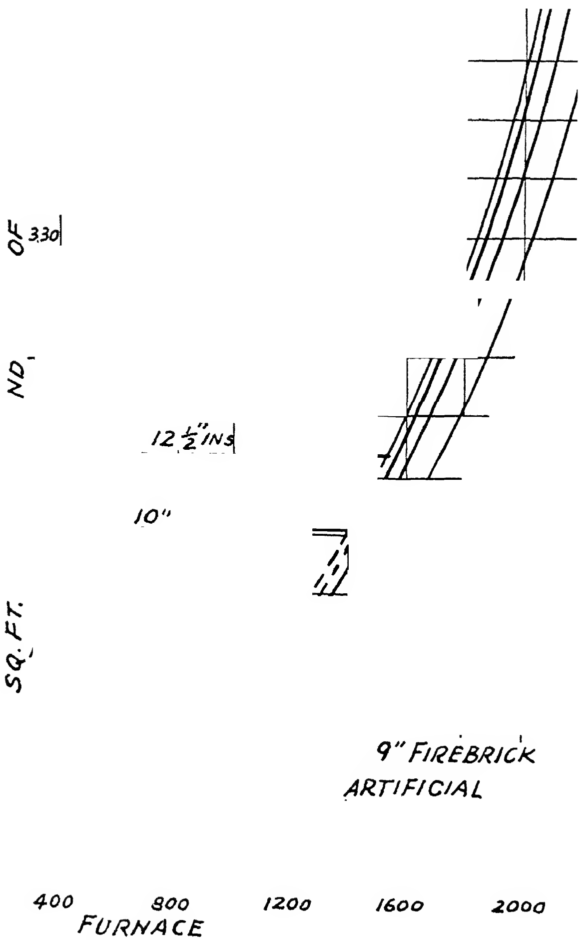


Fig. 62.—Economy from Insulation Applied to 9-in. Firebrick—Artificial Gas.

because the correct insulation for one temperature and fuel is by no means correct for other conditions. However, a consideration of financial management is also involved in every case,

and a time limit within which the insulation must pay for itself in saving must be set from experience in the particular business

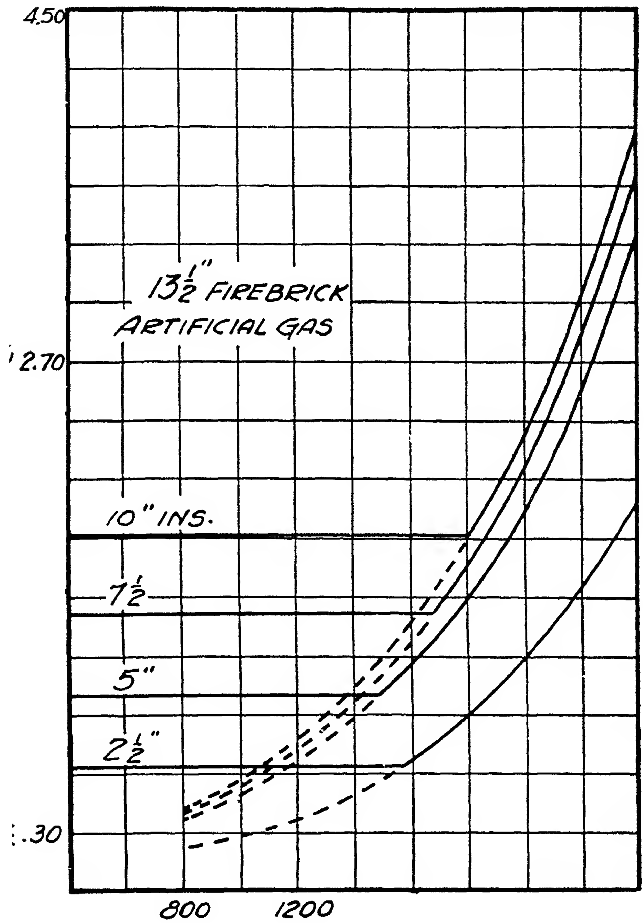


FIG. 63.—Economy from Insulation Applied to $13\frac{1}{2}$-in. Firebrick—Artificial Gas.

for which the furnace is intended, the probable time that the equipment will be operated, and financial policy. Then, for

the existing fuel and temperature conditions the insulation can be so selected as to pay for itself in this time.

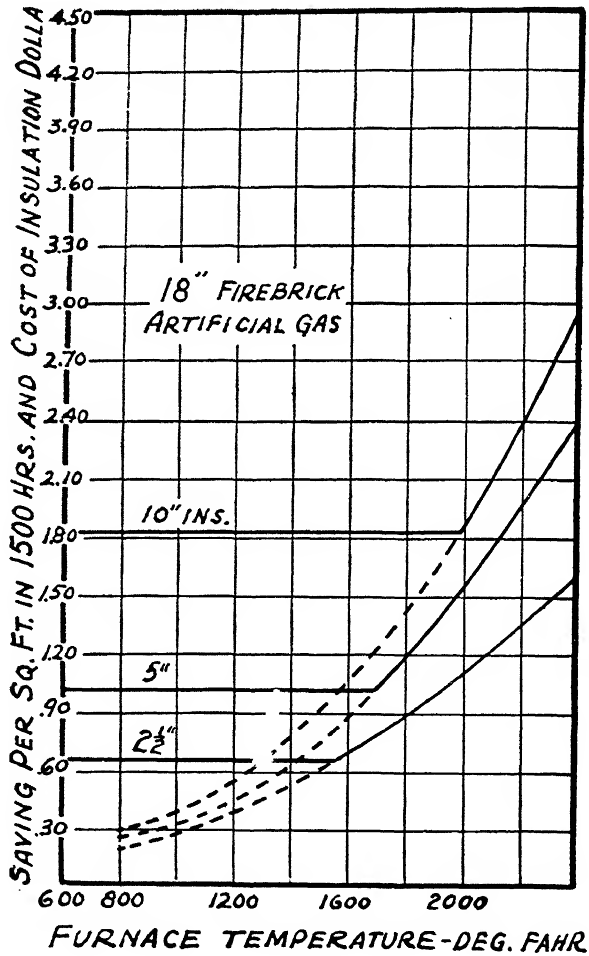


FIG. 64.—Economy from Insulation Applied to 18-in. Firebrick—Artificia' Gas.

In the case of the example of Fig. 55 above, which operates at 1600 deg. Fahr., is oil-fired, and has sidewalls 13½-in. thick, no

insulation will be used, because reference to Table 20 shows that for these conditions 12.8 months would be required for as little

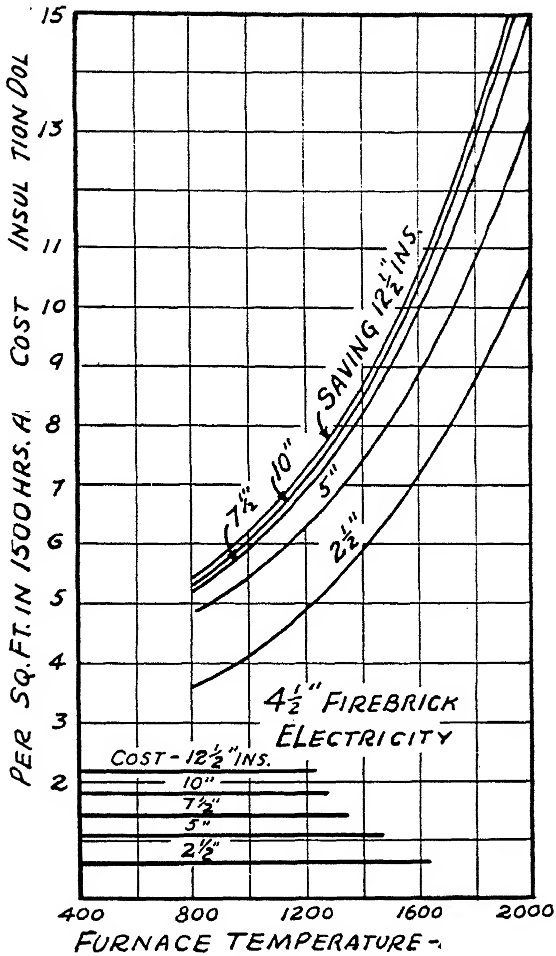


FIG. 65.—Economy from Insulation Applied to 4½-in. Firebrick—Electricity.

as 2½ in. of insulation to pay for itself. For the roof, however, 5 in. will pay for itself in 7.3 months, and may be used. For

the consideration of roofs, the values of Table 20 are slightly high because the steel shell figured into the cost of applying

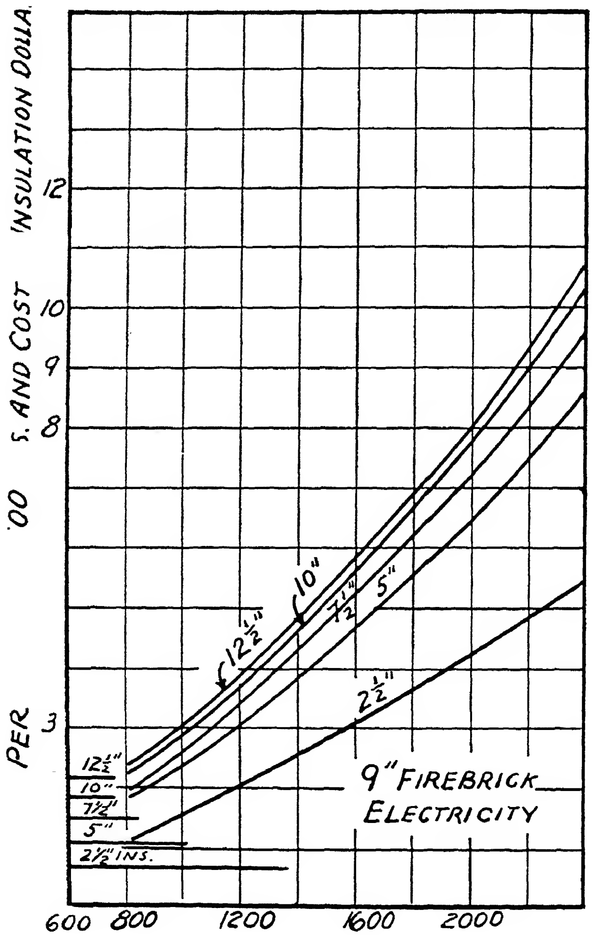


FIG. 66.—Economy from Insulation Applied to 9-in. Firebrick—Electricity.

insulation is never required, but this discrepancy can be neglected without serious error.

TABLE 20

TIME IN MONTHS REQUIRED FOR INSULATION TO PAY FOR ITSELF FOR VARIOUS FUELS, TEMPERATURES, AND THICKNESS OF FIREBRICK AND INSULATION

Firebrick, Inches	Insulation, Inches	Furnace Temperature, Deg. Fahr.						
		1000	1200	1400	1600	1800	2000	2200
		Fuel Oil						
4½	2½	6.74	5.26	4.00	3.03	2.20		
	5	7.73	6.30	5.06	3.87	2.90		
	7½	10.00	7.95	.6.21	4.73	3.55		
	10	12.50	9.87	7.49	5.71	4.35		
	12½	14.86	11.50	8.85	6.76	5.18		
9	2½	16.70	12.00	8.93	7.24	5.48	4.26	
	5	17.69	12.90	9.50	7.28	5.63	4.42	
	7½	21.30	15.80	11.85	8.97	6.92	5.40	
	10	25.90	19.10	14.10	10.65	8.23	6.17	
	12½	30.00	22.00	16.50	12.60	9.60	7.54	
13½	2½	38.40	29.50	17.40	12.80	9.85	7.51	5.56
	5	34.4	22.90	15.85	12.10	9.09	6.86	5.24
		Coal						
4½	2½	14.80	11.60	8.93	6.51	4.80		
	5	18.20	15.10	11.25	8.37	6.19		
	7½	23.00	18.10	13.75	10.40	7.68		
9	2½	38.40	27.50	19.20	14.78	11.00	8.54	5.56
	5	41.30	29.50	21.35	15.90	12.10	9.50	7.10
13½	2½	76.90	54.90	42.60	29.60	22.60	16.70	13.70

TABLE 20—*Continued*

Firebrick, Inches	Insulation, Inches	Furnace Temperature, Deg. Fahr. 1000	1200	1400	1600	1800	2000	2200
		Artificial Gas						
4½	2½	3.07	2.40	1.91	1.37	1.00		
	5	3.54	2.94	2.25	1.67	1.27		
	7½	4.53	3.59	2.66	2.13	1.64		
	10	5.52	4.38	3.37	2.56	1.97		
	12½	6.59	5.19	3.98	3.01	2.29		
9	2½	7.25	5.33	3.96	3.00	2.36	1.83	
	5	8.60	5.89	4.30	3.24	2.50	1.98	
	7½	10.50	7.16	5.23	4.00	3.10	2.39	
	10	12.20	8.50	6.20	4.78	3.70	2.83	
	12½	14.05	10.10	7.30	5.60	4.32	3.30	
13½	2½	13.70	10.10	7.68	5.82	4.31	3.22	2.45
	5	12.62	9.37	7.03	5.33	4.04	3.04	2.32
	7½	16.40	12.35	9.06	6.66	5.13	3.88	3.00
	10	24.90	18.30	13.35	8.25	6.20	4.68	3.58
18	2½	15.40	10.70	7.70	5.83	4.27	3.50	2.93
	5	19.90	14.05	9.95	7.10	5.32	4.11	3.21
	10	27.85	19.75	14.50	10.50	7.75	6.00	4.63
		Electricity						
		0.94	0.80	0.67	0.53	0.44		
	5	1.14	1.00	0.85	0.70	0.57		
	7½	1.44	1.25	1.04	0.86	0.70		
	10	1.81	1.55	1.30	1.07	0.86		
	12½	2.16	1.86	1.54	1.27	1.02		
	2½	2.40	1.83	1.48	1.22	1.04		
	5	2.69	2.06	1.63	1.34	1.12		
	7½	3.27	2.50	2.03	1.67	1.40		
	10	3.82	2.94	2.36	1.94	1.64		
	12½	4.40	3.47	2.81	2.28	1.91		

Refractory Materials of Construction

The refractory materials used in furnace construction may be classified under four headings: fireclay shapes, special bricks, insulation, and plastic refractories. The selection of the proper refractories for the different conditions to be met is important for obvious reasons, one of which is that the necessity for frequent furnace repairs not only interferes with production but increases fuel consumption because of the heat wasted in cooling and heating up the furnace each time repairs are made. An extensive knowledge of refractories is of value in furnace design, and the following discussion is intended to outline the various factors to be considered.

Fireclay Shapes.—This group includes all the shapes of firebrick (fireclay brick) and fireclay tile, and constitutes the greater part of all the brickwork in heating furnaces, as distinguished from melting furnaces, such as open-hearths, where silica brick is mostly used. Silica brick has greater strength at high temperatures than firebrick, but it can be used only where the furnace is operated continuously day and night, including Sundays, because each time that the furnace is cooled serious cracking and spalling occur. This characteristic excludes it from use in practically all heating furnaces. Fireclay, in the form of brick or tile, is used for practically every possible purpose in furnace construction, but for some parts of a furnace the other kinds of brick are better suited, as will be outlined. Fireclay bricks were used several centuries B.C., but in the United States the fireclay beds of New Jersey were probably the first to be discovered. The first firebrick were made from these beds in 1812, and from that time the discovery and utilization of fireclay in large quantities have occurred successively in Pennsylvania, Maryland, Ohio, Missouri, and Kentucky.

The following extract from Circular 282 of the Bureau of Standards states the origin of clays in general:

The argillaceous deposits of the earth's crust can be divided into three types—slate, shale, and clay—all of which were originally derived from igneous rocks; that is, rocks which solidified from the molten state. The

action of weathering agencies on these rocks disintegrated the minerals containing alumino silicates (chiefly feldspars), removed the alkalies and some of the silica, and converted the remaining alumina and silica into hydrous aluminum silicate minerals. Kaolinite and other minerals of this type are the principal constituents of clays.

Although clays are composed essentially of hydrous aluminum silicate minerals, they vary greatly in purity and may contain many minerals carrying silica, alumina, iron oxides, alkalies, lime, and other constituents.

Shales and slates are like clays in chemical composition, but differ markedly from them in appearance and structure. Shales are formed from clays and have become laminated by the pressure of overlying beds of rocks. Slates are formed from clays and shales which have become hardened by high pressure and temperatures due to earth movements.

This publication states that the refractory clays may be divided into three classes: kaolin, flint clay, and plastic clay. The first two classes have low plasticity and a high softening point, and compose the greatest part of the analysis of refractory fireclay material. The plastic clays have a lower softening point, but because of their plasticity they are widely used in small percentages as a bond in refractory materials, to hold the shapes together and make them mechanically strong. The relative percentages of plastic clay and highly refractory clay depend on the purpose for which the brick is made, as do the kinds of other materials (calcined clay, silica, and aluminous materials) which are commonly included in the manufacture of fireclay products. Bricks are sold as first and second grade, depending on the refractory qualities of the clays used.

There are several different methods of manufacture up to to the point of burning in the kiln, which may be briefly outlined as follows:

Hand-made process.—Used mostly for special shapes, large blocks, and some standard 9-in. brick shapes.

1. Clay ground and screened.
2. Tempered with water.
3. Moulded by hand in moulds.
4. Slowly dried on hot floor to prevent cracking during shrinkage.

Stiff mud-repress process.—Extensively used for 9-in. bricks.

1. Ground and screened.
2. Tempered with water.
3. Extruded into column in auger machine.
4. Cut off into blanks.
5. Blanks pressed to size in repress machine.
6. Dried on hot floor.

Soft-mud process.—Not generally used (makes dense, hard bricks).

1. Ground and screened.
2. Tempered with water.
3. Machine, formed directly without repressing.
4. Dried on hot floor.

Dry press method.—Frequently used for 9-in. brick shapes.

1. Ground and screened.
2. Mixed with very little water.
3. Formed in dry press under pressure of ½ to 3 tons per sq. in.
4. Dried on hot floor.

Whatever the process of forming bricks or shapes, after they have been dried on the hot floor to remove the shrinkage water slowly without cracking, they are loaded into a large kiln to be burned for about ten days. The extent, rapidity, and temperature of this burning is of primary importance in determining the properties of the resulting bricks.

The qualities of an ideal fireclay shape are as follows:

1. Perfect consistency in dimensions: length, width, thickness (for even distribution of pressure between bricks).
2. High fusion point (melting of the surface).
3. High softening point (beginning of plastic flow).
4. High strength at high temperatures.
5. Chemical resistance (high resistance to slag penetration and erosion by gases).
6. Low spalling (disintegration under heat).
7. High resistance to abrasion.

The ideal brick has never been developed commercially up to this time, because, with all combinations of the known materials, excellence in some properties is obtained only at the expense of other properties. For example, spalling can be greatly decreased with some clays by coarse grinding, but the strength and resistance to abrasion and slagging of the resulting bricks are low. Silica brick is another example, in that it possesses a high softening point (which makes it best for high-temperature open-hearth roofs which must not give under any conditions), but is extremely poor in practically every other quality. Since the different parts of industrial furnaces require different propties for maximum life, a knowledge of these requirements and of the properties of fireclay bricks is essential to the best design.

This knowledge is best gained from experience in the use of some of the almost infinite number of brands on the market. Published tests of performance are of questionable value, and the best results can be obtained by trying the different kinds and observing their action. Where the bricks are exposed to any considerable temperature, first-grade fireclay bricks should be used, while inside courses can be made of cheaper bricks. Because of the confusion caused in construction by a variety of bricks, more than one type of first-grade brick is seldom used, and the type selected should be adapted to meet the majority of the requirements of the furnace. The following outline shows the relative importance of first-grade fireclay brick properties in the major divisions of furnace construction for temperatures over 1400 deg. Fahr.

As has been stated, actual trial is the best test of the suitability of a type of brick for certain conditions, but there are a number of tests which will assist in forecasting the probable performance by relatively determining the properties which have been outlined above. Reference to publications of the American Society for Testing Materials will give details of the standard tests which that society has adopted for brick specification, but there are simplified tests which will quickly give some idea of the merits of a brick, as follows:

Uniformity of size and perfection of the flat surfaces are

Location	Properties		
	Important	Medium	Unimportant
Arches	Size Strength Spalling Softening point	Fusion point Chemical resistance	Abrasion
Walls	Size Strength	Chemical resistance Softening point Spalling	Abrasion
Bridgewalls	Fusion point Chemical resistance	Strength Spalling Softening point	Abrasion Size
Perforated arches	Size Strength Softening point Spalling Fusion point	Chemical resistance	Abrasion
Underfired hearths and piers	Strength Softening point Abrasion Chemical resistance	Spalling Fusion point	Size
Combustion chambers	Fusion point Softening point Chemical resistance	Size	Strength Spalling Abrasion

important in order that adjacent bricks may be in uniform contact and the pressure between them evenly distributed (also because the cost of construction is reduced by more rapid bricklaying). This quality can be tested by measuring several samples for variation in length, width, or thickness. The usual

commercial allowance is a variation of $\frac{1}{8}$ in. and this tolerance should not be exceeded for best results.

Strength at high temperatures can be compared by laying bricks flat on two supports so that the clear span is about 7 in., and loading with a brick cut to weigh 5 lb. If this arrangement is set up in a furnace which is heated to about 2500 deg. Fahr. and held at that temperature for two hours, a good idea of the comparative strength may be obtained. The temperature in the furnace may be checked by using pyrometric cones. The fusing points of Seger cones are given in Table 21. When subjected to such a load test, a firebrick possessing high strength when hot will not deflect more than about $\frac{1}{2}$ in. at the center, while poor grades will become plastic and completely lose their shape under the load.

An indication of the comparative resistance to spalling may be obtained by the tentative A.S.T.M. test, or by some similar method. In this test, one end of the brick to be tested is heated to about 1600 deg. Fahr. in the door of a furnace, and the heated end plunged into running water for about three minutes. After steaming in the air for five more minutes it is returned again half-way into the furnace. The process is repeated in hourly cycles until the entire end (not the entire half) of the brick has spalled off or can be removed easily with the fingers. The average number of quenchings required to produce this failure in first-grade fireclay bricks is about 10, but the best of them will withstand up to 60 of such shocks while a great many fail by crumbling away at the end on the first quench. Spalling may be due to a number of reasons, including sudden change in volume of a high percentage of free quartz; failure of plastic bond, allowing the refractory portion to crumble; partial conversion of plastic clay to glass, with sudden internal strains; and rapid expansion of one portion of dense structure, where there are no voids to ease such unequal stress. Spalling and failure to hold their strength and shape under load at high temperature are the two most common sources of failure of fireclay bricks in industrial heating furnaces.

Firebricks and fireclay tile weigh about 130 lb. per cu. ft.,

TABLE 21

FUSING POINTS OF SEGER CONES

Number of Cone	Fusing Point, Original Scale		Number of Cone	Fusing Point, Original Scale		Revised Scale *	
	Deg. Fahr.	Deg. Cent.		Deg. Fahr.	Deg. Cent.	Deg. Fahr.	Deg. Cent.
0.022	1094	590	10	2426	1330		
0.021	1148	620	11	2462	1350		
0.020	1202	650	12	2498	1370		
0.019	1256	680	13	2534	1390		
0.018	1310	710	14	2570	1410		
0.017	1364	740	15	2606	1430		
0.016	1418	770	16	2642	1450		
0.015	1472	800	17	2678	1470		
0.014	1526	830	18	2714	1490	2714	1490
0.013	1580	860	19	2750	1510	2750	1510
0.012	1634	890	20	2786	1530	2786	1530
0.011	1688	920	21†	2822	1550		
0.010	1742	950	22†	2858	1570		
0.09	1778	970	23†	2894	1590		
0.08	1814	990	24†	2930	1610		
0.07	1850	1010	25†	2966	1630		
0.06	1886	1030	26	3002	1650	2912	1600
0.05	1922	1050	27	3038	1670	2948	1620
0.04	1958	1070	28	3074	1690	2975	1635
0.03	1994	1090	29	3110	1710	3002	1650
0.02	2030	1110	30	3146	1730	3038	1670
0.01	2066	1130	31	3182	1750	3065	1685
1	2102	1150	32	3218	1770	3101	1705
2	2138	1170	33	3254	1790	3128	1720
3	2174	1190	34	3290	1810	3164	1740
4	2210	1210	35	3326	1830	3191	1755
5	2246	1230	36	3362	1850		
6	2282	1250	37	3398	1870		
7	2318	1270	38	3434	1890		
8	2354	1290	39	3470	1910		
9	2390	1310					

* U. S. Bureau of Standards, Washington, D. C.

† Cones 21 to 25, inclusive, all come down at practically the same temperature.

and the average weight of a standard 9-in. brick is about 7.5 lb. Their expansion with heat is usually neglected, as the maximum expansion does not exceed 0.05 in. per foot at the highest temperatures, and, except for very long furnaces, no allowance need be made for it. The specific heat of firebrick is close to 0.25 B.t.u. per lb. per deg. Fahr. and the conductivity varies from 7.0 B.t.u. per sq. ft. per hour per deg. Fahr. per in. thickness at 800 deg. Fahr. to 12.0 at 2200 deg., the temperatures being average temperatures throughout the brick or tile. The various standard shapes of fireclay bricks are shown in Fig. 67, and common applications are as follows:

Straight 9-in. brick Small 9-in. brick Soap brick Split brick 2-in. brick	Used in the construction of walls and hearths to various dimensions with minimum amount of brick cutting.
Wedge bricks...........	Used in arches 9 in. thick.
Arch bricks.............	Used in arches $4\frac{1}{2}$ in. thick.
Flat-back brick, arch... Flat-back brick, straight	Used in bonding walls and arches.
Skew bricks.............	Used in arch skewbacks and other sloping surfaces.
Featheredge brick.	Used as fillers and in sloping courses.
Circle brick.......	Used in lining stacks or in circular openings.

Fireclay tile are made in rectangular shapes of all sizes to be used in underfired hearths, to span openings in walls (not usually good construction), for covering various small chambers, and for a variety of similar obvious uses. There is also a great variety of special shapes in common use, such as skewback tile, burner tile, tile pier caps for supporting skid pipes, and various kinds of protecting tile for moving hearths in furnaces. The characteristics of the fireclay used in making these tile and the methods of manufacture are the same as for firebricks.

An extremely important feature in refractory life is the method used and the care taken in the laying up of the brick-

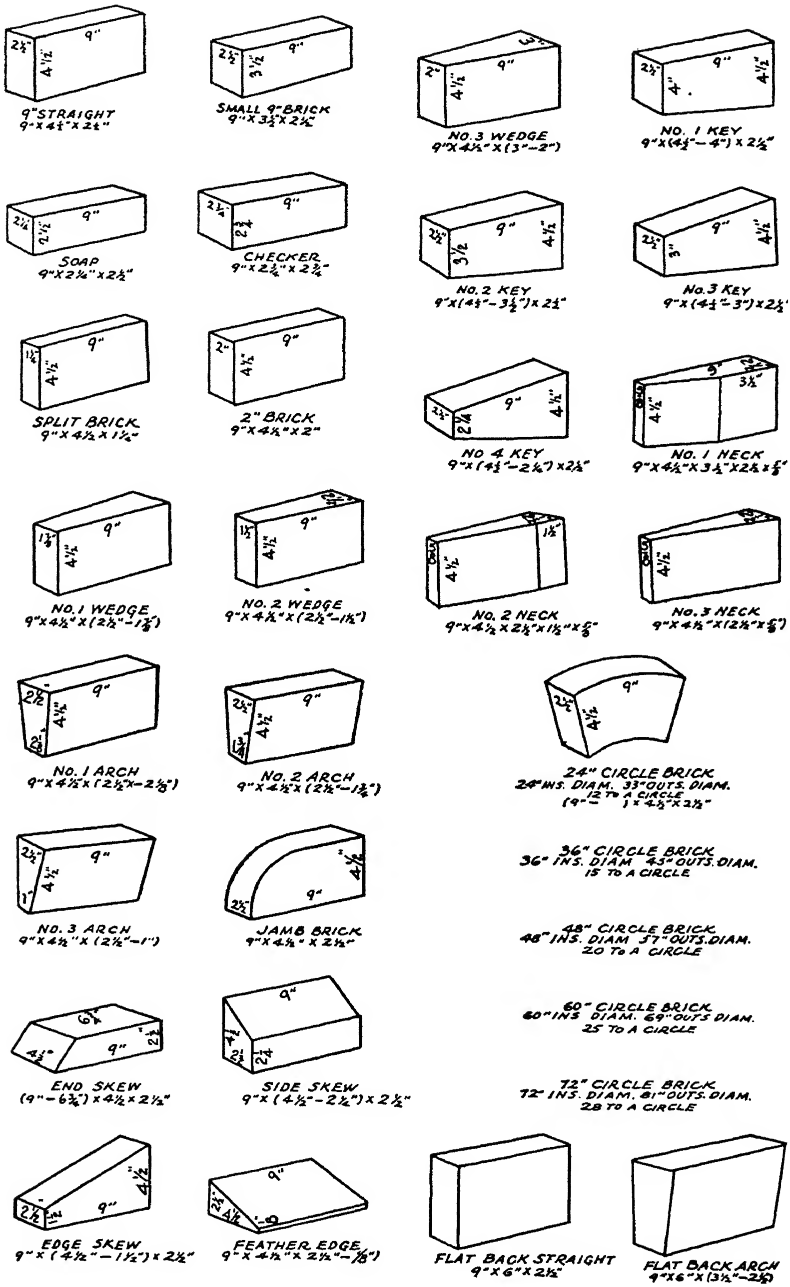


Fig. 67.—Standard Shapes of Fireclay Bricks.

work and in the construction of the joints. The importance of joints was not recognized for a long time, but it is now almost generally appreciated. It has been proved that the life of a furnace lining is limited by the life of the joints, and most builders are insisting that *dipped tee joints* be made, which means that each brick is dipped in thin fireclay and pressed firmly into position, and that the extra clay exuded by pressing the brick firmly into position is plastered over the joint rather than removed by pointing as is done in red-brick house construction. As the high-temperature cements continue to become cheaper they are being more extensively used to replace ordinary fireclay mortar, and their use is always desirable for piers, hearths, burner settings, and other parts where strength at high temperatures is essential. In estimating fireclay or cement quantities, a safe allowance is ½ lb. per brick laid. The quality of fireclay used must be at least as good as that of the firebrick because of the fact that the clay is as important as the brick. If the clay is quickly destroyed, it leaves the edges of the bricks exposed, allowing spalling, erosion, and ultimate failure to occur more rapidly than when the joint remains in position to make, in effect, a monolithic construction.

Special Bricks.—This class includes magnesite, carborundum, chrome, and ordinary red brick, all of which are still used in addition to firebricks for industrial furnace construction.

Magnesite Bricks are used chiefly for high-temperature hearths, as they are very hard and will withstand the action of the iron oxide in the scale which is formed when steel is heated to high temperatures. Magnesite bricks weigh about 10 lb. each and and have a coefficient of expansion of 0.21 in. per ft. at 2200 deg. Fahr. The mean specific heat is about 0.28, and the conductivity varies from 40 B.t.u. per sq. ft. per hour per deg. Fahr. per in. thickness at 800 deg. Fahr. to 25 at 2200 deg. These bricks are laid with special cement and are usually bought in standard 9-in. shapes. The melting point of magnesite bricks is about 3900 deg. Fahr. They spall very easily when subjected to rapid heating and cooling, and ample allowance must be made for the high expansion.

Carborundum Bricks and Tile have a wide variety of uses for places where heat is to be rapidly conducted, as in muffles, carboradiant chambers for muffled heat, or hearths for underfired furnaces, or where great strength at high temperatures is required, as in supporting piers. They are unsuitable for hearths in high-temperature furnaces, because above 1800 deg. Fahr. they are rapidly attacked by the iron oxide in scale. A carborundum brick weighs about 9 lb., and the coefficient of expansion is about the same as for firebrick. The specific heat is from 0.18 at 800 deg. Fahr. to 0.186 at 2200 deg., and the conductivity varies from 69 to 80 B.t.u. per sq. ft. per hour per deg. Fahr. per in. thickness for the same temperatures. This material is used in the form of standard brick shapes or in all kinds of special shapes for special purposes, as pier tile, muffle tile, or recuperator tile. These shapes are laid in special carborundum cement. The melting point is over 4800 deg. Fahr. Spalling of carborundum is very slight.

Chrome Bricks are highly resistant to the action of iron oxide and are sometimes used in the hearths and in the lower walls of high-temperature furnaces. Chromite is chemically neutral, and chrome bricks are frequently placed between magnesite bricks (basic material) and firebricks (acid material) to prevent destructive chemical action. The melting point of chrome bricks is 3730 deg. Fahr., and the coefficient of expansion is 0.20 in. per ft. at furnace temperatures. The conductivity is lower than that of magnesite, and the weight of a brick is about 11 lb. Chrome bricks are laid in chrome cement. Like magnesite, these bricks spall readily and must be heated and cooled slowly to prevent excessive cracking.

Table 22 is a summary of the comparative properties of the various bricks that have been discussed.

Red Bricks are used in furnace construction only for the outside facing of the walls or stacks, or sometimes in foundations. Common red bricks or face bricks, laid up in ordinary cement, are ideal for facing the outside of walls, because of their neat appearance and their great resistance to wear and abuse as compared with firebrick. Where insulation is used, furnace walls

are usually faced with steel or cast-iron plates because of the excessive thickness of walls when red brick is used. On high-temperature furnaces where insulation is not desirable, the use of red brick is preferable to that of metal plates, because the construction is cheaper and because red brick has the same insulating properties as firebrick at low temperatures and therefore increases the efficiency of the furnace. A $13\frac{1}{2}$-in. wall of 9 in. of firebrick and $4\frac{1}{2}$ in. of red brick, for example, will conduct 30 per cent less heat from a 2200 deg. furnace than a steel-faced firebrick wall 9 in. thick, and is cheaper to build.

TABLE 22

PROPERTIES OF REFRACTORY BRICKS

	Carborundum	Silica	Fire-Clay, Grade A	Natural Insulation Brick	Magnesite	Chrome
Weight of 9-in. brick...	9	7	7.5	2.5	10	11
Melting point, deg. Fahr.	4800+	3110	3100		3900	3730
Strength, modulus of rupture in bending test, pounds per square inch, hot...........		161	113		136	22
Coefficient of expansion at furnace temperatures, inch per foot..	0.05	0.18	0.05		0.21	0.20
Specific heat..........	0.18	0.25	0.25	0.25	0.28	0.20
Average conductivity at furnace temperatures, B.t.u. per square foot per hour per deg. Fahr. per inch thickness...	70	10			30	

Insulating Bricks.—There are comparatively few brands of insulating bricks, and information on the different materials from which they are made may be obtained from the manufacturers' catalogue. As to form, insulation may be obtained as

calcined brick, which is hard and strong, and capable of withstanding temperatures up to 1800 deg. Fahr. when directly exposed; plain brick and sheet, which is very soft and not good for temperatures over 1400 deg. Fahr.; and insulating powder, which also must be protected from temperatures in excess of about 1400 deg. The calcined material is sometimes used for the walls of electric furnaces, where there is no flame, and in all furnaces for places where it is difficult to provide adequate firebrick protection for the insulation. Sheet insulation is used on many small standard furnaces, but the standard brick size is the most common form for large furnaces. Powder is seldom used for anything but electric furnaces, because in fuel-fired furnaces the upper temperature limit cannot be easily controlled and the powder is more likely to shrink at high temperatures than the brick form. Also, the usage of a fuel-fired furnace is usally rougher, and is therefore likely to cause leakage and settling of the powder.

An insulating brick will weigh about 2.5 lb., and powder about 15 lb. per cu. ft. of packed volume. The average conductivity of the plain form (including the effect of joints, cracks, and other factors met in actual practice) is about 2.0 B.t.u. per sq. ft. per deg. Fahr. per inch thickness at all temperatures. The conductivity of the calcined form is somewhat higher, as the insulating properties must be sacrificed for the increased strength and hardness of that form. Insulating bricks, as will be repeated later, should always be laid so as to obtain the minimum number of joints, and the courses should always be staggered, or bonded, so that no joint extends clear through the thickness of insulation, in order to reduce heat leakage to a minimum. Insulating powder is frequently used in place of cement in laying the plain form of insulating bricks, while a special bonding cement is used for the calcined form, to take advantage of its structural strength.

Low-temperature ovens, below 600 deg. Fahr., are frequently built with steel sheets on the inside and outside of the walls, which are made entirely of insulating brick or powder. In order to arrive at a safe figure for the heat conducted through such a wall, it is best to use a conductivity of 2.0 B.t.u. per sq. ft. per

hour per deg. Fahr. per in. This figure will account for shrinkage, settling, joints, or cracks which may appear after a period of operation.

Plastic Materials.—The use of this form of refractory material is increasing as the quality is improved by the manufacturers, and it is now extensively used for many purposes in place of firebrick and insulating brick. The purposes of all such materials is to produce a monolithic (one-piece) structure, and the common uses include furnace hearths, special shapes which are difficult to build from bricks without excessive cutting, door linings, fillers for uneven and sloping portions in construction, and repairs to walls, roofs, and door jambs. The material, whether it is *refractory* (heat-resisting) or purely *insulating* in nature, should set and dry rapidly, in addition to possessing the qualities necessary to resist the heat, abrasion, or stresses to be met in different applications. Plastic refractory materials developed for use in furnace hearths have been found equal to or better than firebrick (some forms are made from chrome ore and replace chrome and magnestic bricks) in heat resistance, and have lasted much longer in service than brick hearths. The plastic material is frequently chemically neutral and resistant to iron oxide, and is superior mechanically to the brick construction, where bricks are frequently pulled loose. Also, heat and slag cannot readily penetrate a plastic hearth, because the material is less porous than firebrick and there are no joints. Plastic insulating materials (usually 4 parts of insulating material to 1 part of Portland cement by volume) are used almost exclusively for lining the doors of furnaces below 1800 deg. Fahr. temperature, and here again the greatest advantage is that there are no individual bricks to become loose and pull out as there are in a brick-lined door. Special shapes can be made by tamping into moulds, and will frequently save labor in addition to making a better construction than if bricks were cut and fitted. Entire ovens—roof, walls, door, and floor—have been built by tamping plastic insulation, mixed with a small proportion of concrete, into wooden forms. In the construction of doors, additional strength is given to the plastic lining by using wire

mesh inside the lining. The sheet of wire mesh is firmly fastened to the door frame to prevent the lining from falling out. Plastic materials are all exceedingly strong and hard when dried and burned by a slow initial heating. Plastic insulating material is a better insulator (about 4.0 B.t.u. per sq. ft. per hour per deg. Fahr. per in.) than firebrick but not so good as insulation in brick or powdered form.

Plastic materials are all made in the form of powder and mixed with water to make the consistency desired for handling. The weight of plastic refractory powder required to construct one cubit foot of volume averages 185 lb., and of insulating materials 55 lb. The cost of refractory plastic material is from three to four times that of equivalent firebrick, and of plastic insulating cements about $2.50 per cu. ft. of finished volume, which is about 15 per cent less than the cost of calcined insulating brick installed, which it most resembles. For the heavy service in rolling-mill and forging-furnace hearths, the plastic refractory surface should be 6 to 9 in. thick, depending upon the area and the abrasion to be resisted. Firebrick is used under the plastic surface to make total thicknesses as previously given in this chapter. In spite of their comparatively high cost, plastic materials are the best for many furnace requirements.

With this outline in mind of the various kinds of refractory material used in furnace construction, we shall now consider the more important points to be watched in the detailed construction of furnace refractories, as far as it is possible to consider these in such a general discussion.

Mechanical Construction of Refractory Parts

Arches.—The sprung arch is the usual construction for heating furnaces, and it is made up of the combination of 9-in. straight bricks and standard tapered bricks, which will produce a perfect circle of radius equal to the span of the arch. For example, if the span of the arch is 5 ft., the circle of which the arch is a sector will have a 10-ft. diameter, and a complete circular ring will be made from 76 No. 1 arch bricks and 87 straight

9-in. bricks for an arch of $4\frac{1}{2}$-in. thickness; and of 91 No. 1 wedge bricks and 83 straight 9-in. bricks for an arch of 9-in. thickness. These figures can be obtained from any brick maker's catalogue. Table 23 gives the combination of arch bricks and wedge bricks with straight bricks to form complete circles of the diameters usually found in furnace construction. When the arch span is made equal to the radius, the included angle of the actual arch sector is 60 deg., and the number of bricks required for each ring of the arch will be one-sixth of the number required for the complete circle.

The rings of an arch are usually laid up with straight joints across the arch between rings, because this construction is easier to repair; but sometimes the rings are toothed into each other, or bonded, for additional strength. It is essential that the shapes making up each ring fit perfectly, because otherwise adjacent bricks will have only partial contact and cracks will be left on either the inside or the outside of the arch. In either case, the arch will be greatly weakened and the possibility of a brick dropping out and allowing the entire ring to collapse will be great. In constructing a sprung arch, a wooden form is first set up between the skewbacks (arch abutments) of the walls. A ring of the proper shapes, as outlined above, is then laid together from wall to wall, and ground by rubbing together, if necessary, to insure good contact surfaces at all joints across the ring. The bricks are then laid up in clay from both sides until one brick space is left at the center. A key brick of such a size and shape as to be a fairly tight fit is then prepared and driven into the space to complete the ring. On very wide arches, two key bricks are sometimes driven into each ring about one-third of the distance from each skew. On long furnaces, a space of about $\frac{1}{4}$-in. is left between rings at intervals of about 6 ft. in the furnace length, to allow for expansion.

When small flue openings are to be left in an arch, a construction such as that shown in Fig. 68*a* can be used; while if the opening is very large the arrangement of Fig. 68*b*, utilizing circle bricks, is the best for strength and durability.

Doors or flue openings of any kind in a furnace wall should

TABLE 23

BRICK SHAPES REQUIRED FOR ARCH CONSTRUCTION
9-In. Arch Brick

Inside Diameter		Shapes Required				
		Number 3 Arch	Number 2 Arch	Number 1 Arch	Straight	Total
Ft.	In.					
0	6	19	....	....	....	19
1	0	12	15	....	....	27
1	6	4	30	....	....	34
1	9	....	38	....	....	38
2	0	....	34	8	....	42
2	6	....	26	23	....	49
3	0	....	19	38	....	57
3	6	....	11	53	....	64
4	0	....	4	68	....	72
4	3	....	....	76	....	76
4	6	....	....	76	4	80
5	0	....	....	76	11	87
5	6	....	....	76	19	95
6	0	....	....	76	27	103
6	6	....	....	76	34	110
7	0	....	....	76	42	118
7	6	....	....	76	49	125
8	0	....	....	76	57	133
8	6	....	....	76	64	140
9	0	....	....	76	72	148
9	6	....	....	76	79	155
10	0	....	....	76	87	163
10	6	....	....	76	94	170
11	0	....	....	76	102	178
11	6	....	....	76	109	185
12	0	....	....	76	117	193

TABLE 23—*Continued*

9-In. Wedge Brick

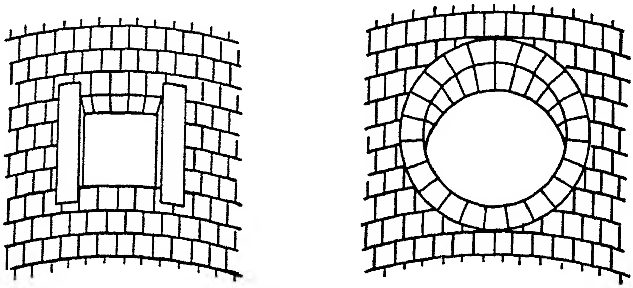
Inside Diameter		Shapes Required			
		Number 2 Wedge	Number 1 Wedge	Straight	Total
Ft.	In.				
2	3	57			57
2	6	49	11		60
	0	38	30		68
	6	26	50		76
	0	12	71		83
	6		91		91
	0		91		99
	6		91	15	106
	0		91	23	114
	6		91	30	121
	0		91	38	129
	6		91	45	136
	0		91	53	144
	6		91	60	151
9	0		91	68	159
9	6		91	76	167
10	0		91	83	174
10	6		91	91	182
11	0		91	98	189
11	6		91	106	197
12	0		91	113	204
12	6		91	121	212
13	0		91	128	219
13	6		91	136	227
14	0		91	143	234
14	6		91	151	242

TABLE 23—*Continued*

9-In. Wedge Brick—*Continued*

Inside Diameter		Shapes Required			
		Number 2 Wedge	Number 1 Wedge	Straight	Total
Ft.	In.				
15	0	....	91	158	249
15	6	....	91	166	257
16	0	....	91	173	264
16	6	....	91	181	272
17	0	....	91	188	279
17	6	....	91	196	287
18	0	....	91	203	294
18	6	....	91	211	302
19	0	....	91	218	309
19	6	....	91	226	317
20	0	....	91	233	324
20	6	....	91	241	332
21	0	....	91	248	339
21	6	....	91	256	347
22	0	....	91	263	354
22	6	....	91	271	362
23	0	....	91	278	369
23	6	....	91	286	377
24	0	....	91	293	384
24	6	....	91	301	392
25	0	....	91	308	399
25	6	....	91	316	407
26	0	....	91	323	414
26	6	....	91	331	422
27	0	....	91	338	429
27	6	....	91	346	437

always be arched as shown in Fig. 69*a* or Fig. 69*b*, rather than spanned by a tile as shown in Fig. 69*c*, because tile does not possess sufficient strength to span even small openings without cracking at high temperatures (over about 1600 deg. Fahr.), and is expensive to repair. Figure 70 illustrates the method of constructing an arched door. Arched openings will last as long as the wall above them, and may be made either circular or flat by shaping the bricks as shown in the illustrations. Special interlocking tiles, based on the same principle, have recently been introduced commercially for building flat-arched openings



a *b*

FIG. 68.—The Construction of Flues in Arches.

without the cutting that is required when standard brick shapes are used. The maximum span for flat-arched openings, such as that shown in the illustration, is about 4 ft., and above that span a cast-iron, alloy, or water-cooled beam must be used to support the wall over the opening.

A comparatively recent but very important development in arch construction for heating furnaces is the suspended arch, which has been used for many years in boiler-furnace design. There are several arrangements, one of which is shown in Fig. 71. Alternate rows of roof tiles are hung by clips and hanger rods from the supporting beams, and the remainder of the rows are held up by these suspended rows. The arch may be sloped or made flat by variation of the suspension parts, so that any desired shape of roof may be obtained. The suspended con-

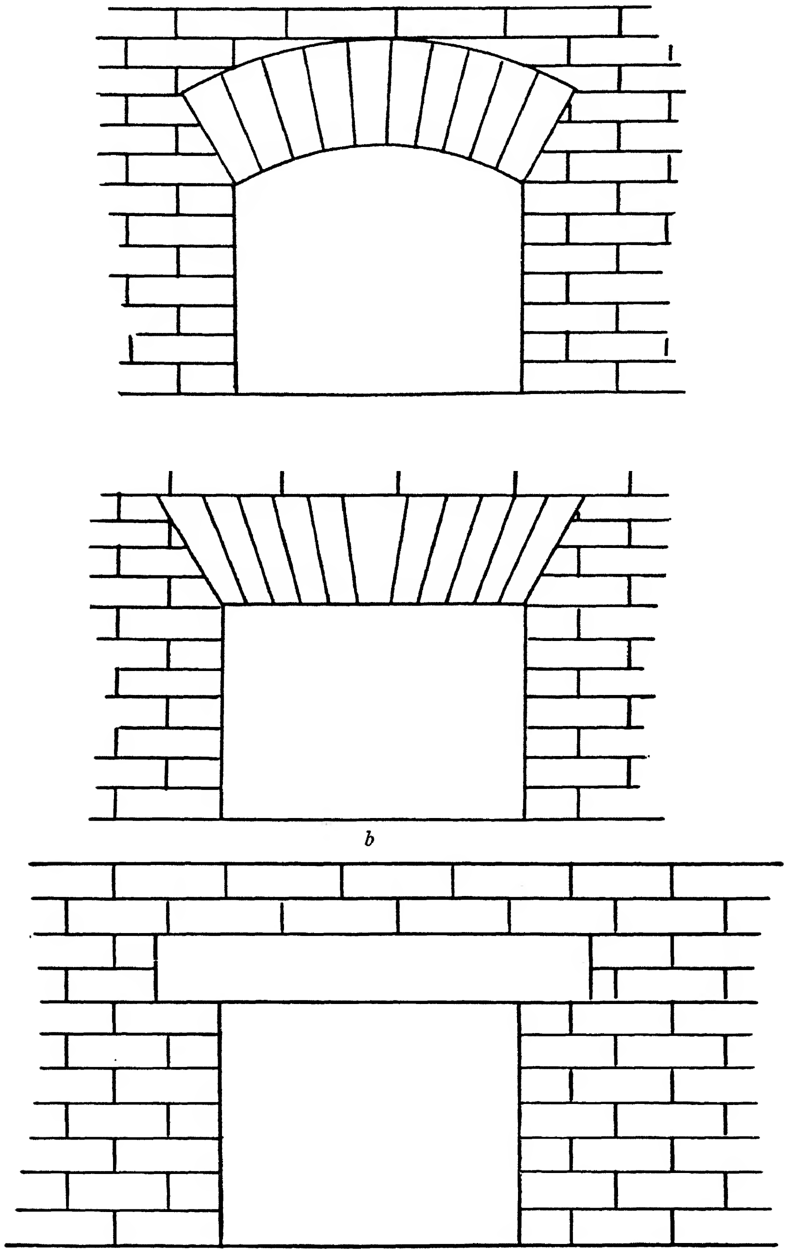


Fig. 69.—The Construction of Openings in Walls.

struction is more expensive than the sprung-arch construction and usually has no advantages for spans under about 8 ft., but for

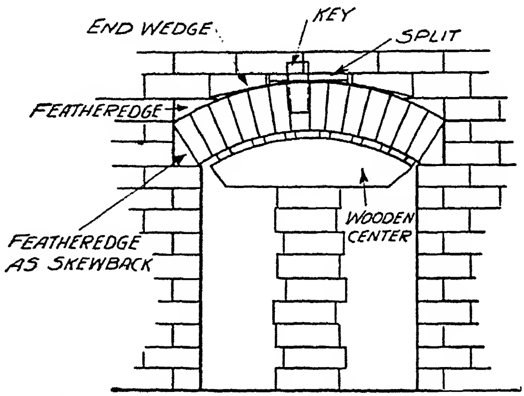


FIG. 70.—Method of Constructing an Arch.

large furnaces it has a number of distinct advantages. Sprung arches can be constructed with spans up to 16 ft., but the thrust

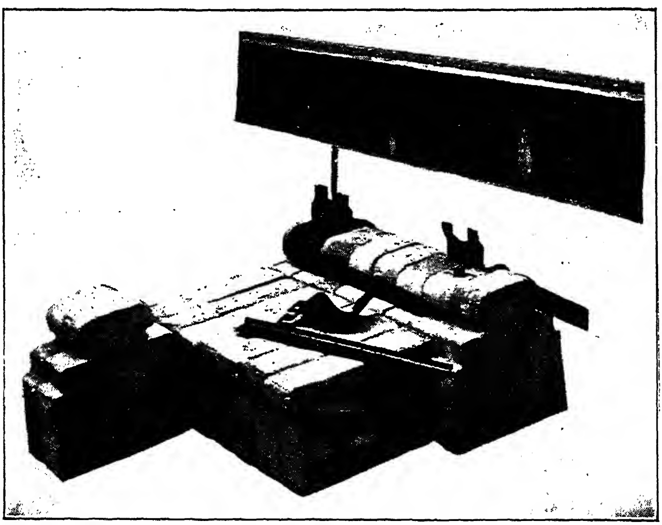
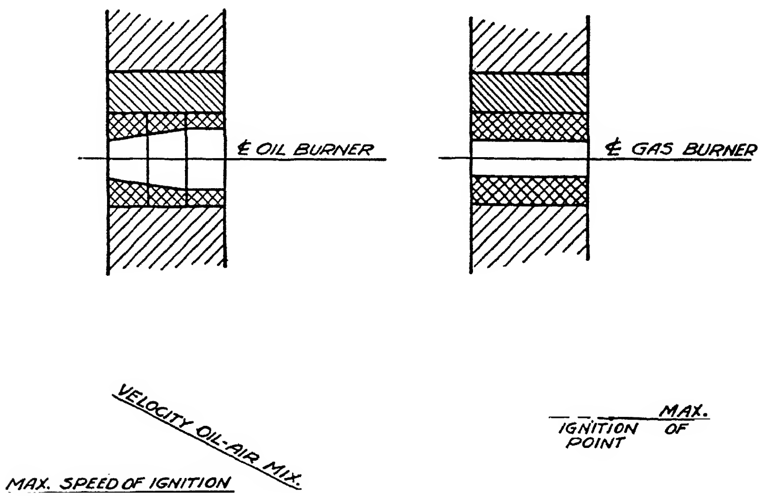


FIG. 71.—Details of One Form of Suspended Arch.

of wide arches, which must be $13\frac{1}{2}$ in. in thickness, is enormous, so that the furnace binding must be extremely heavy. Also, the

rise of a 16-ft. arch from skew to crown is more than 2 ft. and the furnace roof is usually unnecessarily high at the center, which means lowered efficiency of heat transmission to the heating material. With the suspended arch, a thickness of 9 in. may be used for any span, and the roof may be made the same height across the furnace. Also, there is no side thrust, and the furnace binding must be only heavy enough to support the dead



a.

FIG. 72.—Burner Openings for Oil and Gas Fuels.

weight of the arch. These arches have been very successfully used on high-temperature furnaces for rolling mills with spans of 30 ft.

Burner Openings.—Gas, oil, and powdered-coal burner openings are best made from special tile set in the furnace wall with high-temperature cement, because of the concentrated heat frequently developed at this point. The burner tile should be spanned above by a fire clay tile to support the wall above the burner tile in case any replacement of the burner tile is necessary. Figure 72 shows typical circular burner openings through a $13\frac{1}{2}$-

in. wall for oil and gas fuels. The burner ports for oil are always flared, because the speed of ignition of fuel oil is low, and it is therefore essential to reduce the velocity of the oil-air mixture from the burner as much as is possible by allowing expansion, in order that ignition may not occur too far from the wall. With gas, on the other hand, the speed of ignition is high, and if a flared opening is used the gas-air mixture from the burner will light inside the burner tile and burn it out in a short time. With a straight opening, the velocity is not reduced by expansion until the gas leaves the port. Burner tiles are usually made $4\frac{1}{2}$ in. thick to accommodate different thicknesses of walls, which are usually a multiple of that dimension.

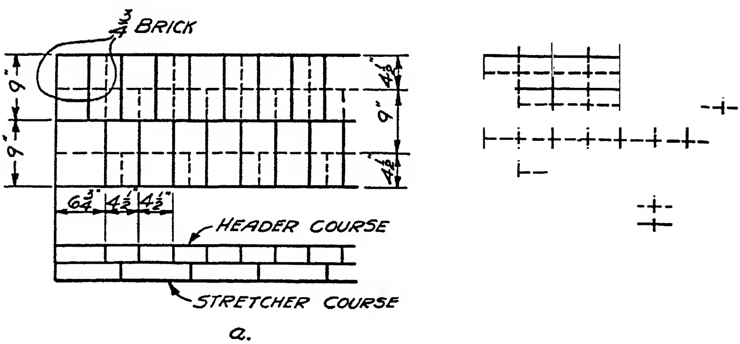


FIG. 73.—Examples of Bonding in Brick Construction.

Walls.—The firebrick portion of furnace walls is usually built of flat courses of brick to obtain the thickness in multiples of $4\frac{1}{2}$ in., and the courses are bonded together to obtain the maximum strength. Bond in brickwork means a tie or link, obtained by so overlapping the bricks that heat or slag penetrating between two bricks will not strike a joint in the next course. This is accomplished by the use of *headers* and *stretchers*, a header being a brick laid so that its length is perpendicular to the face of the wall, and a stretcher being a brick laid with its length parallel to the face of the wall. Figure 73 illustrates two common bonds used in furnace construction, the heavy lines denoting one course and the dotted lines the alternate course. Figure 73*a* shows a straight 18-in. wall. By three-quarter brick is meant a straight

brick that is cut to any length more than one-half the normal length and less than full length. It will be observed that at some points in this illustration the solid lines and the dotted lines coincide; this means that at these points the bricks are not properly bonded in a vertical direction. However, for a wall this is not serious, because only the horizontal bonding between the faces is important. In the case of a furnace bottom, however, the conditions are reversed; the brickwork must be bonded up and down, as shown in Fig. *73b*, while the lateral bonding is not important.

Furnace dimensions are made multiples of brick dimensions wherever possible, to save cutting labor, and although the use of splits allows considerable variation, their use is eliminated wherever possible to save handling labor. Firebrick is always extended through to the furnace shell behind the skewbacks when insulation is used, because insulation bricks do not have sufficient strength to transmit the thrust of the arch to the furnace binding, and the skewbacks may give, and allow the arch to fall, unless firebrick is used.

Whereas firebricks are generally laid flat, insulating bricks are always laid on edge to reduce the number of joints, so that insulation thickness varies in multiples of 2½ in. Where there is more than one course in thickness, the horizontal joints are again staggered so that heat cannot penetrate between adjacent joints.

As previously stated, flues in furnace walls should be separated by at least 4½ in. of firebrick from any insulating brick or red brick. Figure 74 shows sectional views of the construction of flues in a typical insulated wall, and Fig. 75 shows a flue in a wall which is faced on the outside with red brick. The first example is for the case of a sidefired furnace and shows a method of conserving brick and space by building around the flues on the inside of the wall, thus saving 4½ in. in the thickness of the wall, and reducing the combustion chamber only between burners where it does not matter. When skewback tiles or bricks are adjacent to a flue, as shown in these illustrations, they must be long enough to span the flue in one piece. Flues in this location are limited to 13½ in. width by the strength of these tiles.

Overhanging walls may be constructed by stepping out each successive course of bricks beyond the course below it.

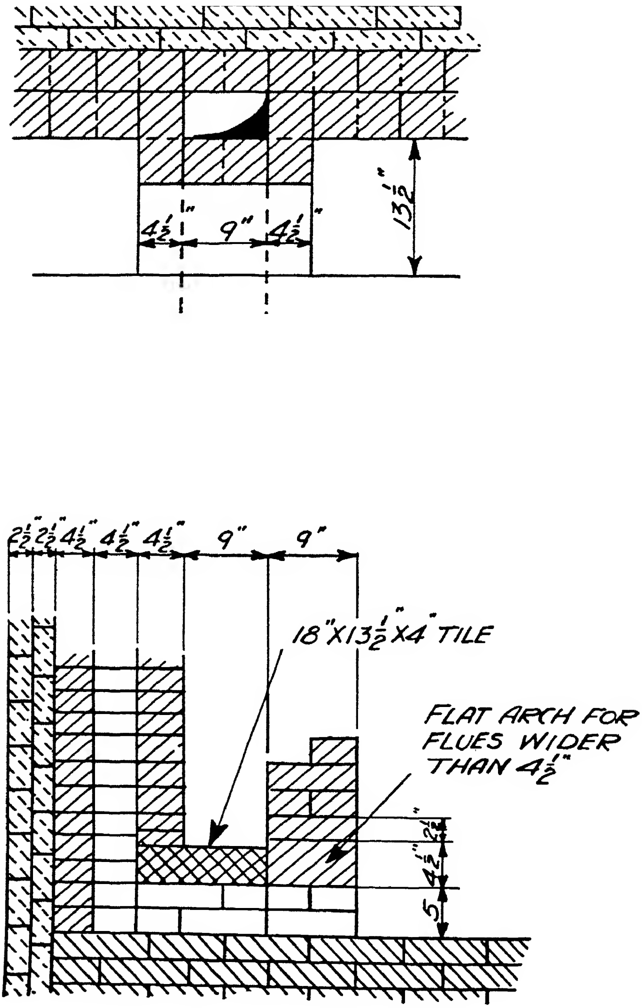


FIG. 74.—Flue Arrangement in Sidefired Furnace.

This procedure is called corbeling, and the resulting wall is known as a corbeled wall. A maximum amount of increase

of 1½ in. with each 2½-in. thick course should not be exceeded for good strength and durability.

During the initial heating of furnaces that are built with red brick on the outside of the walls, openings frequently appear in the joints of this facing, caused by the expansion stresses of the hot firebrick inside. These are not serious and can be remedied by pointing with cement on the outside after the furnace has been in operation for some time. In laying firebrick for walls, and in other furnace construction, thin clay should be used and the joints should be made as small as possible. Heavy joints should never be used to make brick courses come to desired dimensions. For burner openings, door arches, door jambs, or other places where there is excessive temperature or abrasion, a good high-temperature cement should be used in place of fireclay in laying firebricks, as previously stated.

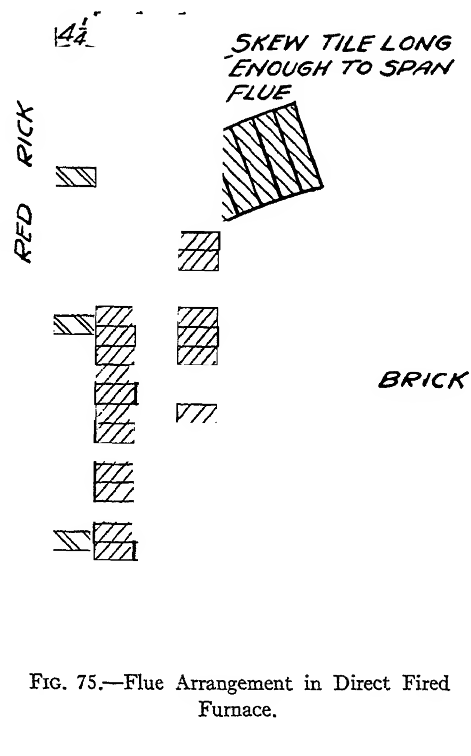


FIG. 75.—Flue Arrangement in Direct Fired Furnace.

Hearths.—Hearths are usually made up of combinations of flat and *rowlock* (bricks on edge) courses. The lower courses are laid flat and the top courses on edge, because in this position they are less likely to be dragged out of the furnace by material scraping over them. Further to insure against this contingency, the top rowlock course is often laid with the bricks at an angle

of 45 deg. to the furnace sides. Where magnesite or chrome bricks are used for the top course, strips of wood about $\frac{1}{8}$ in. thick must be laid between all bricks. These strips burn out and allow for the excessive expansion of the material. When plastic material is used for furnace bottoms (or for door linings, small furnace linings, or similar purposes), the instructions of the manufacturers should be carefully followed to insure the most satisfactory results.

In estimating the number of bricks required for furnace construction, the general rule is 17 fireclay straight bricks per cubic foot of brickwork volume. For walls, 7 bricks are required per square foot of $4\frac{1}{2}$-in. thickness, 14 per square foot of 9-in. thickness, 21 per square foot of $13\frac{1}{2}$-in. thickness, and so on. Fireclay mortar or special cement requirements average $\frac{1}{2}$ lb. for each fireclay brick laid. For laying red bricks, 2 bags of cement, $\frac{1}{2}$ barrel of lime, and $\frac{1}{2}$ cu. yd. of sand are required for each thousand bricks laid. The cost of laying firebricks varies with the cost of labor and with the intricacy of the construction, but a good figure for quick estimating is \$50 for labor per thousand bricks. The number of bricks required for arches has been previously given.

Furnace Foundations

Portable furnaces are built on a foundation of structural shapes rigidly braced and held together so that the furnace can be moved; but most furnaces of any size are permanently built in position and require a permanent foundation. On account of the considerable amount of furnace below hearth level in the underfired type, the thickness of foundation required is not great, but in most types only the hearth thickness of brick is below the hearth level and the remainder is foundation to floor level. The hearth height above floor level varies in furnaces for different purposes, the average being about 30 in. for convenient charging of material. Concrete is the cheapest and most common material for foundations, although red brick makes an excellent foundation and is frequently used where the bricks are

already available. Concrete construction costs somewhere in the neighborhood of $30 per cu. yd. finished, which will give an idea of the approximate cost of this part of the furnace. The thickness of the total foundation, including the portion below floor level, depends upon the nature of the soil, and is figured, as are all concrete pads, from an estimate of the weight of the furnace to be built upon it.

Concrete will not withstand much heat without disintegration, and must be adequately protected from the heat of the furnace, as has been stated. Slots are frequently left in the top of the foundation to allow circulation of air between the foundation and the hearth brickwork. Foundations should always be made as smooth as possible on top, since the extra labor required to do this is not so expensive as the bricklaying labor required to lay an even first course of brick on a rough foundation top. Also, where the hearth slopes, it is cheaper to slope the concrete foundation than it is to leave the foundation flat and build a sloping course of brickwork. Reinforcing rods are desirable in a furnace foundation, especially at the edges, where the foundation is exposed to hard knocks and rough usage.

This completes the discussion of refractory design and construction in heating furnaces, a discussion which must of necessity be very general because of the wide variation in the details of the many forms of furnaces. Two furnaces are seldom alike in detail, and there are many satisfactory ways of obtaining good results in design, but in this chapter it has been the intention to point out the general rules which should be followed in order to insure against the more serious forms of failure. In the next chapter we shall consider the various metal parts and auxiliary equipment necessary to complete the construction of the average furnace.

CHAP'

DESIGN OF METAL PARTS AND AUXILIARIES

In the preceding chapter the design of refractories entering into the construction of an industrial furnace was discussed. In this chapter we shall complete the consideration of the actual construction with a study of the various metal parts required in a furnace and of the design of these parts.

The variety of metal parts in the many kinds of furnaces is too great to allow consideration of each part in detail, but it is possible to select the most common and most typical parts and, by careful examination of these, point out the methods by which most furnace parts may be satisfactorily designed. As will be shown, the well-known rules of structural and machine design can be applied directly in some cases, while in others modifications must be made to take care of the effect of heat.

A list of typical metal parts includes the structural-steel furnace binding, cast-iron furnace binding, stationary and moving parts exposed to furnace heat, and water-cooled parts. With this list in mind we shall consider, first, the physical properties of the metals used in furnace construction, and then the selection and application of these metals for the design of different parts. Finally, some attention will be given to the auxiliary mechanical equipment used with furnaces, such as door-lifting mechanism, pushers, fuel-oil and gas burners, and piping.

Physical Properties of Metals

The principal metals used in furnace design include structural steel, cast iron, cast steel, and high-temperature alloys.

Stuctural Steel.—The forms of structural steel most commonly required are I-beams, channels, angles, tee-bars, plates, and

rods; and the weights and strengths of all of these forms can be readily obtained from tables such as those given in *Mark's Handbook* or the Carnegie Steel Company's *Pocket Companion.* Most structural steel is made in basic open-hearth or Bessemer furnaces, and has a carbon content of from 0.20 to 0.25 per cent. The average ultimate strength in tension which can be used in the design of furnace parts is 60,000 lb. per sq. in. when cold, and this figure must be greatly modified for the effect of heat according to the use to which it is put, as will be shown later. Average allowable fiber stress is 16,000 lb. per sq. in. when cold, and this value also decreases where the steel is exposed to any heat. The ordinary forgings used for cranks and other members contain about the same percentage of carbon, and the same values may be used. Cold-rolled steel used for axles and various shafts contains from 0.35 to 0.45 per cent carbon, and has a tensile strength, when cold, of 80,000 lb. per sq. in. and an allowable unit stress of 40,000 lb. per sq. in.

The effect of heat on metals is greatly to reduce their strength, this effect increasing as the temperature rises, until a point is reached where the metal becomes so plastic that it does not have sufficient strength to support its own weight. Neglect of this fact is the cause of most failures of metal parts in furnaces, and its importance cannot be overestimated. Figure 76 shows the effect of temperature on the strength of structural steel, as compared with other metals. In the case of steel, oxidation becomes very active before the point of complete softness is reached, and prevents the use of steel at high temperatures, even in sections of sufficient dimensions to overcome the loss of strength. This oxidation, or scaling, begins at a temperature of about 1100 deg. Fahr. and makes steel unsatisfactory for any use inside a furnace that is operated at a temperature exceeding this figure. Steel weighs about 0.29 lb. per cu. in.

Iron and Steel Castings.—Ordinary soft gray-iron castings, as made in a cupola and used in the construction of machinery, constitute the greater part of all furnace castings. This metal weighs about 0.26 lb. per cu. in., and can be cast in almost any size. The strength of cast iron is comparatively low, the aver-

age tensile strength, when cold, being about 20,000 lb. per sq. in.; Fig. 76 shows the effect of temperature on its strength. The principal reasons for the use of cast iron are, first, that it does not oxidize as rapidly, lose its strength as quickly on heating, or warp nearly as badly as structural steel when exposed to heat;

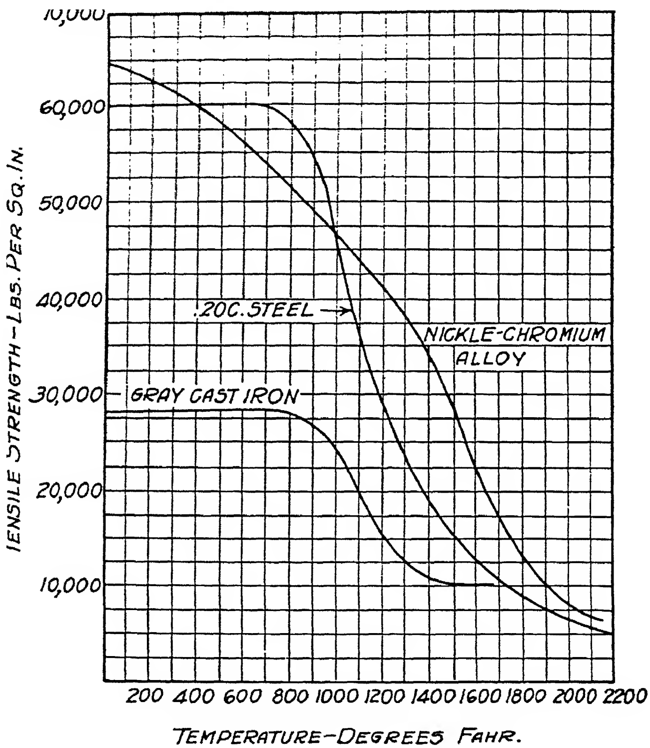


Fig. 76.—Effect of temperature upon the strength of metals.

and, second, that it is a cheaper material for many shapes, such as sheaves, counterweights, door frames, and many other parts.

The first reason accounts for the almost universal use of cast iron around furnace openings, because, although these parts become extremely hot at times, they will not warp or oxidize if properly designed. Oxidation limits the use of cast iron inside of a furnace to temperatures not exceeding about 1600 deg. Fahr.

At this temperature, cast iron has lost considerable strength, but oxidation is so slow that castings of sufficiently heavy sections for strength requirements can be made to last for at least six months in service. Cast iron expands about 0.06 in. per ft. at 1600 deg. Fahr., and has an additional permanent growth of as much as $\frac{1}{8}$ in. per ft., which must be allowed for in the design of cast-iron parts for use inside of furnaces. The thermal conductivity of cast iron is about 330 B.t.u. per sq. ft. per hour per deg. Fahr. per in. thickness.

Malleable-iron castings are not frequently used in furnace design, except in the construction of low-temperature furnace chains, because at temperatures above about 1100 deg. Fahr. the malleable properties are lost and the characteristics become similar to those of ordinary cast iron. Malleable iron is ideal for some mechanical parts outside of the furnace which must withstand twisting, bending, or shocks that would be too great for the brittle nature or ordinary cast iron. Castings of this material have a tensile strength of about 40,000 lb. per sq. in., and should not be machined, because the greatest strength is at the surface of the casting. It should be mentioned at this point that all castings of all kinds should be left rough if possible where they are exposed to heat, because they are better able to withstand oxidation and warping in this state than when they are machined.

Cast steel is stronger than cast iron and slightly better able to resist oxidation. It weighs about 0.29 lb. per cu. in., and has an average tensile strength of about 60,000 lb. per sq. in. when cold. The thermal conductivity is about 400 B.t.u. per sq. ft. per hour per deg. Fahr. per inch thickness. Cast steel is hard enough to withstand considerable wear and abrasion, and is frequently used for wearing plates inside of furnaces where the temperature does not exceed about 1600 deg. Fahr. The expansion and growth of cast steel may be represented by the values given above for cast iron.

High-temperature Alloys.—Iron castings and steel have been used in furnace construction ever since furnaces were first used, but heat-resisting alloys have been in extensive use for less than

ten years. In that short time, however, they have revolutionized furnace design, and it will not be out of place at this point to explain more clearly why this is true. About twenty years ago it was discovered that some metals possess the property of resisting oxidation at elevated temperatures, and that when these metals are alloyed with iron they give this property to the alloy to varying but always considerable extents. This immediately suggested the use of these alloys for the simple parts which were used in furnaces at that time. The cost of these alloys, however, was much greater than that of steel or cast iron, and it required a great deal of time to prove the advantages of replacing these cheap materials. Progress in this direction was also retarded by over-optimistic promises and consequent failures. It was not until about 1915 that designers and operators became interested to any great extent in the use of these alloys, but since that time progress has been extremely rapid. The alloys themselves have been constantly improved to combine reasonable cost, good machineability, ductility, resistance to oxidation, strength, and good foundry practice; and each successful application has suggested new and daring possibilities for mechanical handling of material in furnaces, with consequent labor saving. All kinds of good and bad ideas have been tried out, and there have probably been more failures than successes; but from this frenzy of experimenting have emerged a reasonable popular attitude and knowledge of these metals and a large number of sound methods of design.

Two metals—nickel and chromium—are the only ones found to any extent in heat-resisting alloys, and the opinion of authorities on the subject seems to be that these metals will remain the best in the future. Both nickel and chromium have the property of resisting oxidation at elevated temperatures, but they impart different physical properties to the alloy. Chromium increases the physical strength but tends to make the alloy brittle, while nickel is low in physical strength but improves the ductility and toughness of the resulting metal.

Four combinations—iron and chromium, iron and nickel, chromium and nickel, and all three together—will include prac-

tically the entire field of alloys for use at high temperatures. One of the few exceptions is a process by which iron-base metals are treated with aluminum to produce the property of resisting oxidation. In each alloy there are various impurities, the total of which seldom exceeds 5 per cent of the analysis. The selection of the proper combination in any case, as well as the proper relative proportion of constituents in the combination, depends upon the requirements, and even when acid and chemical resistance is neglected, no one alloy is ideally suited for all conditions. The reaction of alloys with chemicals, such as the fatal reaction of nickel with sulfur, is a specialized study in itself.

The variation in the properties of commercial alloys may be seen from Table 24, which is not a complete list of the good heat-resisting alloys but is sufficient to give a good idea of typical properties.

The values given in the table are all averages supplied by the manufacturers, and will vary somewhat with conditions met in their application and with variations in the details of their casting or rolling, but the fair agreement between these independent sources of data gives a good general idea of the properties of these alloys. The values for tensile strength are given for 1800 deg. Fahr., and if used with an adequate safety factor, as will be explained, will give reliable results. An important feature which is frequently overlooked in the consideration of the strength of materials at high temperatures is the effect of time. A design which is apparently standing up well the first day or week will frequently fail completely in the first month of its operation, because the metal is gradually weakening. The expansion of heat-resisting alloys is about $\frac{1}{4}$ in. per ft. at 1800 deg. Fahr., and the heat content in B.t.u. per pound at any temperature is about the same for most alloys as for steel, so that the values of Chapter V may be used. Attention should be called to the fact that the values for conductivity given in the table are for a thickness of one foot. For a thickness of one inch, the values must be multiplied by 12.

In connection with engineering formulas required for design, a value for safe working fiber stress will be required, and the

TABLE 24

AVERAGE PROPERTIES OF HEAT-RESISTING ALLOYS

Alloy	Approximate Composition			Conductivity at 2000 Deg., B.t.u. per Square Foot per Hour per Deg. Fahr. per Foot Thickness	Tensile Strength at 1800 Deg. in Cast Form	Density, Pounds per Cubic Inch	Maximum Working Temperature, Deg. Fahr.	Forms Available
	Fe	Ni	Cr					
Nichrome.....	26	60	13	35	20,000	0.29	1900	Wire, strip, sheet, rod, cast, forgings.
Nichrome IV....	......	80	20	35	20,000	0.29	1900	Wire, strip, rod, electrical resistors.
Fahrite CS....	73	......	26	57	12,000	0.29	1800	Castings only.
Fahrite N—1..	44	37	17	57	16,000	0.29	2000	Castings only.
Q-Alloy.......	12	68	22	40	25,000	0.29	2300	Cast, sheet, rod.
X-ite.........	40	——60——		40	....	0.29	2000	Castings only.
Hybnickel.....	48	35	15	60	20,000	0.29	2100	Cast, forgings.
Misco.........	46	36	16	....	....	0.29	1800	Cast, rolled rounds.
Duraloy.......	68	......	30	50	10,000	0.27	2100	Cast, sheet, rod, wire, tubing, forgings.
Duraloy B.....	80	......	18	....	10,000	0.27	1400	Same as Duraloy.
Ascaloy 44.....	67	9	24	....	18,000	0.28	2250	Cast, sheet, bars, rivets.
Fire Armor....	18	60	20	87	13,000	0.29	1900	Castings, sheets.
Calite A.......	......	......	......	66	18,000	0.28	2000	Castings only.

following values, which include an adequate safety factor, may be used satisfactorily for most of the high-grade alloys:

Temperature, Deg. Fahr.	Fiber Stress, Pounds per Square Inch
1300	6000
1500	4000
1600	1700
1800	500
2000	100

This completes the survey of the strength of materials, and we can now consider the details of actual design and application of these materials to various furnace parts.

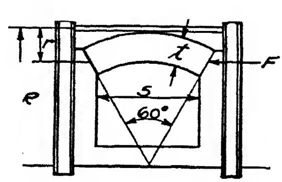
Application and Design of Metal Parts

Structural Members.—The principal parts of a furnace that are made from structural steel are buckstays, reinforcing members in the refractories, tie rods, supporting members, and sheet-steel casings.

The factors in the determination of furnace buckstays, which are the vertical members in the furnace binding, are the arch span, roof thickness, spacing between buckstays, and furnace temperature. The chief purpose of the side buckstays on a furnace is to withstand the thrust of the roof arch, so that as the furnace heats up and the arch expands, there will be no movement of the skewback upon which the arch rests. The calculation of arch thrust has been very completely treated in *Industrial Furnaces*, Vol. I, by Professor Trinks, and the method of calculation there described has been condensed by the writer to the following formulas for quick determination of buckstays and tie rods. The formulas for the thrust of an arch against its skewbacks (total thrust in pounds of an arch d feet long between buckstays), the area of tie rods required, and the section modulus

necessary in the buckstays are given in Fig. 77. In these formulas a fiber stress of 12,000 lb. per sq. in. has been used for both the tie rods and the buckstays, to allow for the heat to which these members are usually subjected. The tables in Fig. 77 give the tie rod and buckstay sizes corresponding to the areas and section moduli obtained by the formulas. As an

d, Distance between Buckstays, Ft.
t, Arch Thickness, Ft.
S, Arch Span, Ft.
R, Distance between Tierods, Ins.
r, Upper Tierod to Line of Arch Thrust, Ins.
f, Temperature Factor:—
 2 —up to 1600° F. Furnace Temp.
 $2\frac{1}{2}$—1600° F. to 2000° F.
 3 —Above 2000° F.
F, Reaction Thrust of Arch.
M, Section Modulus Required in Buckstays.
A, Tierod Area Required.



$$F = 127dtsf$$

$$A = \frac{127dtsf(R - r)}{12000R}$$

$$M = \frac{dtsf(Rr - r^2)}{95R}$$

Tierods Diam.	Tierods Area
$\frac{3}{8}''$	0.11
$\frac{1}{2}$	.20
$\frac{5}{8}$	.31
$\frac{3}{4}$	.44
$\frac{7}{8}$	.60
1	.79
$1\frac{1}{4}$	1.23
$1\frac{1}{2}$	1.77

BUCKSTAYS

ize	Two Channels		One I-Beam	
	M	Wt. per Ft.	M	Wt. per Ft.
3	2.2	8.2	1.9	7.5
4	3.8	10.8	3.6	10.5
5	6.0	13.4	6.1	14.8
6	8.6	16.4	8.7	17.3
7	12.0	19.6	12.1	20.0
8	16.2	23.0	17.1	25.5
9	22.6	30.0	24.8	35.0
10	36.2	50.0	31.7	40.0

FIG. 77.—Determination of Buckstay and Tierod Sizes.

example, if a required area of 0.50 sq. in. and a necessary section modulus of 5.8 cu. in. are found by the formulas, the tie rod should be $\frac{7}{8}$ in. in diameter, and the buckstay may be built of two 5-in. channels each weighing 6.7 lb. per ft., or of one 5-in. I-beam weighing 14.75 lb. per ft. The end buckstays of a furnace are usually made of members of the same weight as the side buckstays.

The equations of Fig. 77 are for an arch resting upon skewbacks at angles of 60 deg. (radius of arch equal to span), and since arches must occasionally be designed to be either flatter or higher, with consequently different skew angles, the derivation of the equation for the reaction, F, should be understood. The weight of the arch t feet thick, d feet long, and with radius equal to span will be:

$$d \times t \times \frac{2\pi \times \text{span}}{6} \times 140 \text{ lb./cu. ft.}$$

This density is higher than the actual density of fireclay brickwork and is used to offset the error resulting from the use of the inside radius of the arch, instead of the mean radius through the center of the arch brickwork. Exact calculation may be made by using a radius of $\left(s + \frac{t}{2}\right)$ and an exact density for the arch material used. One-half of the roof weight is supported by each skew, and for the 60-deg. skew angle the relation between the vertical weight and the horizontal thrust is $\sqrt{3} : 1$. F is therefore:

$$dt \times \frac{2\pi s}{6} \times 140 \times \tfrac{1}{2} \times \sqrt{3} = 127\,dts,$$

when the arch is cold. To take care of the expansion when the arch is heated, a factor is used as shown in Fig. 77, and the formula for arch thrust on the skewback becomes:

$$F = 127\,dtsf.$$

Figure 78 gives an idea of the use of steel members in strengthening the furnace refractories. A skewback support, either angles, or a channel as shown, is always used behind the skewbacks to distribute the arch thrust between buckstays. The size of this member may be calculated by the usual formula for distributed load on a beam. The formulas for beams subjected to various loadings are commonly used in furnace design and will be frequently referred to in this chapter, so that Fig. 79,

giving the formulas for maximum moments (in inch-pounds) to which beams are subjected with various loadings, is given at this point. In practically all cases of the comparatively simple furnace calculations, the moments may be determined by these formulas. The maximum moment so obtained is then divided by the allowable fiber stress, to obtain the section modulus (in cubic inches) necessary to withstand the stress. The fiber stresses to be used have already been discussed in this chapter. To allow for possible exposure to heat, an allowable stress of 12,000 lb. per sq. in. is used for steel furnace binding (allowable fiber stress of steel is 16,000 lb. per sq. in. when cold). The necessary section modulus having been determined, the size of section required may be obtained from handbooks.

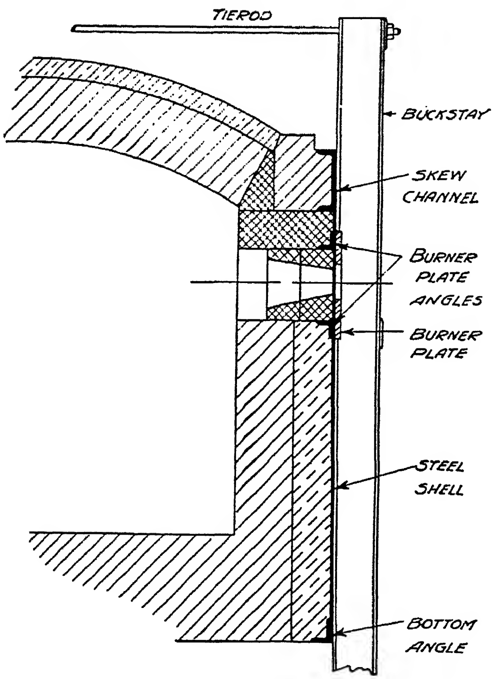


FIG. 78.—Construction of Skewback Support.

In the case of the skewback support, if a furnace has an 8-ft. span, 9-in. arch, 1800 deg. working temperature, and buckstays 3 ft. apart (buckstays should seldom be more than 3 ft. apart), the thrust of the arch, F, will be:

$$3 \text{ ft.} \times \frac{9}{12} \text{ ft.} \times 8 \text{ ft.} \times 2\tfrac{1}{2} \text{ (factor)} \times 127 = 5700 \text{ lb. (Fig. 77).}$$

This force can be assumed to be distributed evenly over 3 ft. of

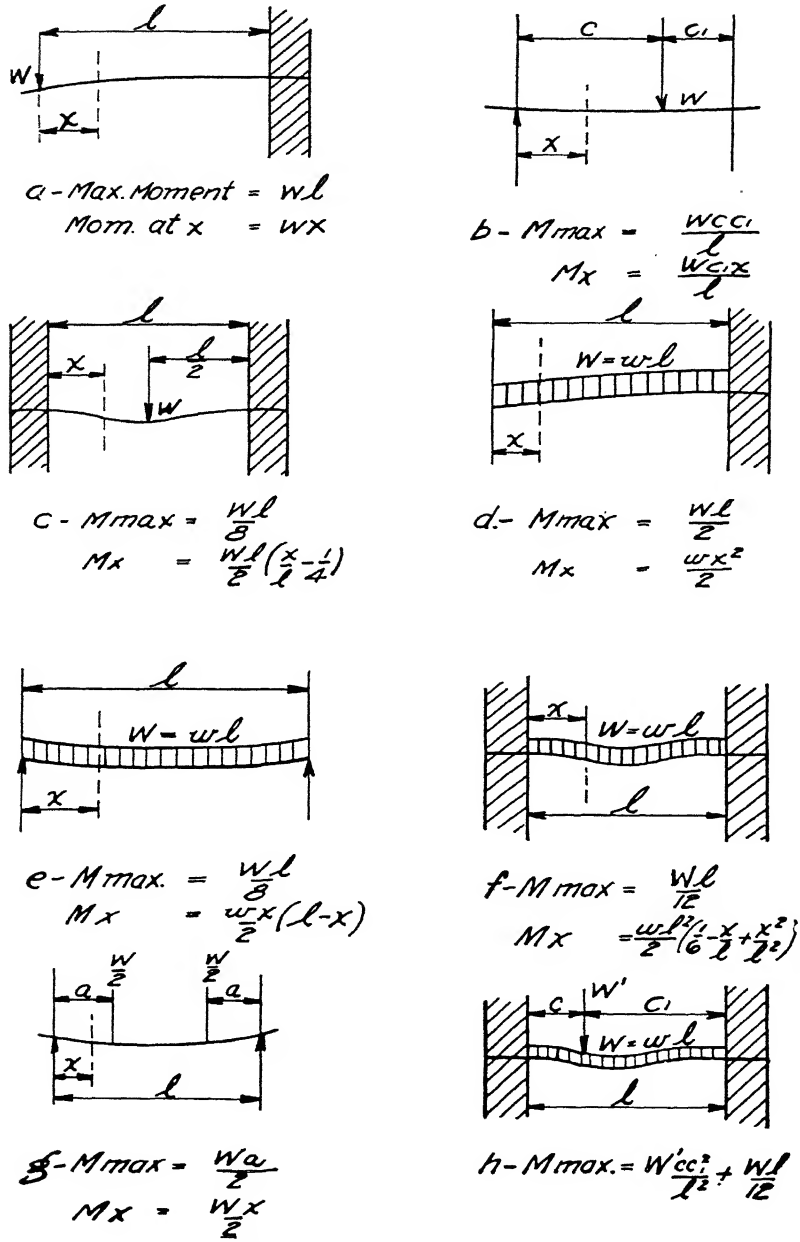


FIG. 79.—Moments in Variously Loaded Beams.

skewback channel, and the bending moment (Fig. 79*e*) will be:

$$\frac{Fl}{8} = \frac{5700 \times 36 \text{ in.}}{8} = 25{,}600 \text{ in.-lb.}$$

A value of 12,000 lb. per sq. in. is used for the fiber stress, and the required section modulus is:

$$\frac{25{,}600}{12{,}000} \quad 2.13 \text{ cu. in.}$$

Consulting tables of the properties of structural shapes for a channel having this section modulus on an axis through the legs, we find that a 12-in. channel of 30 lb. weight per foot will be required.

Most other steel strengthening members are simply to protect the brickwork and keep it in place, or to provide for bolting the sheet-steel casing or burner plates to the outside of the furnace, and they need not be determined by any calculations.

Supporting beams include those required for raising doors, holding up roofs of the suspended type, and similar purposes. Again the standard formulas for structural design apply, and several examples will best illustrate the method of calculation.

Suppose that, in the case of a suspended arch, beams made up of two channels arranged back-to-back are located 2 ft. apart through the length of the furnace, to support a roof of 20-ft. span and 9-in. tile thickness. Then the weight supported by each beam will be:

$$2 \text{ ft.} \times 20 \text{ ft.} \times \frac{9}{12} \text{ ft.} \times 125 \text{ lb./cu. ft.} = 3750 \text{ lb.}$$

This load will be uniformly distributed by hangers at close intervals, so that the maximum bending moment will be:

$$\frac{3750 \text{ lb.} \times 240 \text{ in.}}{8} = 112{,}500 \text{ in.-lb.}$$

Using a fiber stress of 12,000 lb. per sq. in., the required section modulus is:

$$\frac{112{,}500}{12{,}000} = 9.4 \text{ cu. in.}$$

On an axis perpendicular to the web center, a 7-in. channel weighing 9.75 lb. per ft. has a section modulus of 6.0 cu. in., so that beams made up of two such channels would have a modulus of 12.0 cu. in. and would be satisfactory. It is good design to allow something for contingency, however, and beams of two 8-in. channels weighing 11.25 lb. per ft. would have a section modulus of 16.1 cu. in., which would take care of all possible shocks and give a rugged appearance for a small additional expenditure.

Another example of the method of calculation used in the determination of the size of supporting members will be given for the shaft which supports the door on a furnace such as is shown in Fig. 25 of Chapter III. Suppose that this door is 5 ft. wide and 3 ft. high, and weighs 1800 lb. (including counterweights). The span of the shaft between supports is 7 ft., and the two points of suspension of the door are 3 ft. apart and each at a distance of 2 ft. from the adjacent shaft bearing. The shaft is made of cold-rolled steel.

The standard formula for the maximum bending moment in a beam under two equal and symmetrical loads is one-half of the total load times the distance from loads to adjacent ends (Fig. 79*g*), so that in this case the moment will be:

$$1800 \times 24 = 21{,}600 \text{ in.-lb.}$$

Using an allowable stress of 25,000 lb. per sq. in. for cold-rolled steel exposed to some heat, the required section modulus is:

$$\frac{21{,}600}{25{,}000} = 0.87 \text{ cu. in.}$$

The expression for the section modulus of a shaft of circular cross-section on an axis through the center is $\frac{R^3}{4}$, where R is the radius, so that in this case the required radius is very nearly 1.0 in. This will mean a 2-in. diameter shaft, but, owing to the shocks in raising and lowering the door, a $2\frac{1}{2}$-in. diameter shaft should be used if a good rugged design is desired.

Many steel parts of the usual industrial furnace cannot be designed by mathematical computation, but are determined from experience and good sense. An example is the steel shell on the outside of many small portable furnaces and on larger furnaces which are supplied with insulation. The function of this casing is to protect the refractories from bumps and abuse, and it must be made heavy enough to do that effectively. For the small furnaces, 14-gauge sheet in flanged sections, or small flat sections stiffened by angles at intervals not exceeding 4 ft., is good construction. On large furnaces, $\frac{3}{16}$-in. steel plate bolted to the buckstays makes a solid and lasting construction.

Cast-iron and Cast-steel Members.—This class of metal furnace parts includes doors, plates around furnace openings, furnace rails, wearing plates, and pots and muffles. Exact calculation is impossible for most of these parts, and their design is based on experience with the behavior of the metals under different heat conditions.

Doors are most frequently made of cast iron, except in low-temperature ovens, where structural doors are most commonly found. Furnace doors must withstand considerable heat from leakage and from heat conduction through the lining, and cast iron is well suited to withstand the oxidation and warpage which results, provided it is properly designed to reduce its tendeney to crack when heated. Rounded corners of ample radius should be used in all designs, and care should be taken to avoid the sudden junction of thick and thin sections. For small doors not exceeding about 4 ft. in any dimension, a metal thickness of $\frac{1}{2}$ in. may be used, while a specified thickness of $\frac{3}{4}$ in. is better for the sides and top of larger doors. The bottom is usually made $\frac{1}{4}$ in. thicker, to take care of the shock when the door is closed. Most doors are designed for a refractory lining about 7 in. thick, consisting of refractory insulating cement for furnaces operating at temperatures below 1800 deg. Fahr., and of firebrick for higher temperatures. The metal casing is usually turned in for about 1 in. around the periphery of the door to help to hold this lining in place. Doors are held against the furnace by various

kinds of wedges into which they drop when closed, and by slotting the holes for the supporting eyebolts at the top of the door. By moving the chain suspension points in these slots, the pressure of the top and bottom of the door against the furnace can be adjusted so that the door hangs properly.

Furnace openings should always be surrounded by cast iron to prevent warping or burning of any steel parts, and to strengthen the refractory corners of the opening. Small doors, such as those of small heat-treating furnaces or the trouble doors on large furnaces, may be surrounded by a one-piece plate of of cast iron, which should be at least $\frac{3}{4}$ in. thick for long life. A rectangular opening in a cast-iron plate tends to crack at the corners when heated, but this can be helped by the arrangement shown in Fig. 80*a*. Large door frames should be made in four pieces (frequently termed upper front plate, two cheek plates, and sill plate) and about $\frac{1}{8}$ in. should be left between these pieces for expansion. These pieces are held against the furnace by buckstays, which are protected from heat by the projecting ribs at the sides of the opening. The brickwork should always be $4\frac{1}{2}$ in. inside the metal opening at the sides and top, and flush with the outside face of the cast-iron frame. This is essential for long life of the metal and is shown in detail in Fig. 80.

Furnace rails are frequently made from cast iron when the furnace temperature does not exceed 1600 deg. Fahr. They are used in pusher-type furnaces for heating all kinds of materials, which are carried in boxes or pans when the size and shape is not suitable for direct pushing. These rails are made in all shapes, depending upon the requirements, which usually include a wearing surface, a guiding edge, and a portion available for binding into the furnace refractories. Common forms have sections in the shape of a cross, tee, or ell, and sometimes the rails are almost wide enough to cover the furnace hearth. Figure 81 shows several common forms. Where the rails are of complicated section they are difficult to cast straight, and are made in sections, which are firmly imbedded in the brickwork with an allowance between sections for expansion and growth of the cast iron when heated. Rails should be made in one piece where pos-

sible, and simple sections can be made in lengths up to 12 ft. One end of a one-piece rail should always be free to allow for expansion when heated. In designing cast-iron rails to withstand any bending action, a fiber stress of 1700 lb. per sq. in. at 1600 deg. Fahr. should not be exceeded, as has already been

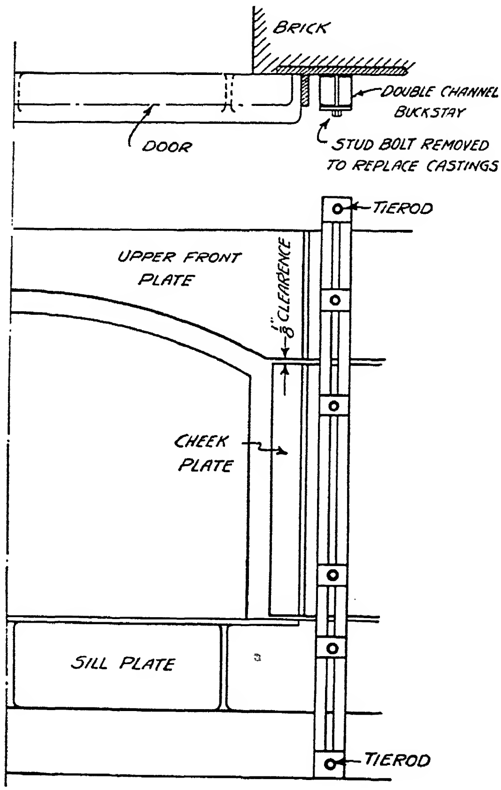


FIG. 80.—Construction of Door Frames—Note Protection by Brick.

stated in this chapter. Rails should seldom be designed to span a distance exceeding 9 in. between supports, because of their low strength when hot.

Wearing plates are imbedded in furnace brickwork where there is excessive abrasion from material charged into or discharged from the furnace. They are commonly used in high-

temperature rolling-mill furnaces of continuous design where the heavy billets are charged into the furnace from the side. These plates are made at least 2 in. thick and will last a long time because the temperature at that part of such a furnace

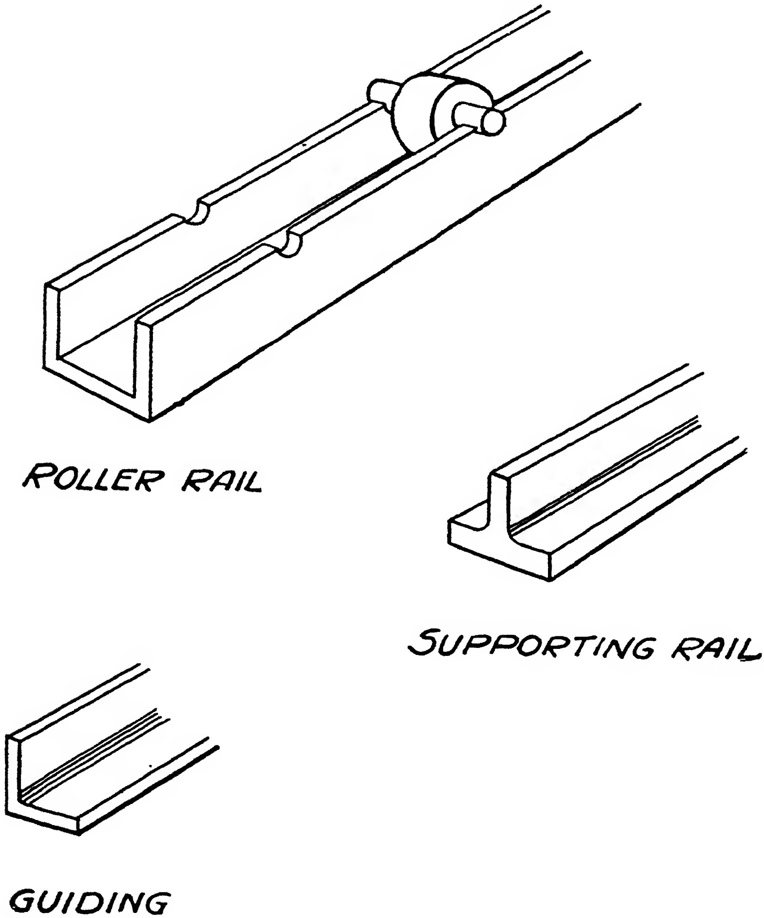


FIG. 81.—Forms of Metal Furnace Rails.

seldom exceeds 1600 deg. Inclined discharge chutes are another common location for wearing plates or bars.

The requirements of metal pots and muffles are walls as thin as is consistent with strength required, and with resistance to

oxidation and chemical action when present. For temperatures up to 1300 deg. Fahr., good cast iron is the best material for pots, but above that temperature strains can be set up which cause cracks. Between 1300 and 1600 deg., cast-steel or pressed-steel pots are usually the best. Above 1600 deg., alloy will frequently pay for itself in a reasonable length of time, because of the longer life resulting from the greater resistance to oxidation. Pots and muffles should not be made thicker than is necessary, because a greater temperature is required on the outside to force the same amount of heat through a thicker section, which means that more fuel is required (because of greater radiation through furnace walls and more sensible heat lost in escaping flue gases) and that the metal is more subject to oxidation. On the other hand, they must be strong enough to withstand the strains to which they are subjected. Cast-iron or cast-steel pots are seldom designed for fuel-fired furnaces with a bottom less than $1\frac{1}{2}$ in. in thickness or greater than 2 in., while the sides vary from 1 to $1\frac{1}{2}$ in. thick at the bottom to $\frac{1}{2}$ to 1 in. thick at the top, depending upon the depth of the pot. This applies to pots with an interior temperature greater than 1000 deg. Fahr. For lower temperatures, as in oil tempering pots, the metal may be made with from $\frac{1}{2}$ to $\frac{3}{4}$ in. thickness throughout. An ample radius should be used for all corners (at least equal to the greatest metal thickness) to avoid sharp edges and abrupt changes of section.

Alloy Members.—Alloy parts in furnaces may be either stationary or movable. The first class includes such members as rails (see Fig. 81; roller rails of alloy are extensively used), muffles, guides, hearth plates, boxes, pans, and so on, while the second class includes chain conveyors, roller hearths, moving fingers, rotating drums, and rabble arms.

The design of all of these parts has until recently been based entirely on experience gained from observation of the alloys under different conditions of heating. This form of knowledge will always be essential to the proper design of high-temperature mechanism, but the introduction of reliable data on the properties of these alloys is increasing the successful use of engineering

methods and reducing the number of failures. The physical properties of some of the high-temperature alloys have been given in this chapter, and examples of the application of these data to several problems will give some idea of the method of rational design which should be followed wherever possible in the determination of alloy parts to withstand high temperature. The principal features to be considered are (1) character of the part, (2) nature of strain and strength required, and (3) effect of expansion and contraction.

The character of the part determines of what kind of metal it should be made (whether plain casting, machined casting, rolled shape, or forging) and the selection is based on the properties of these different forms of metal. Plain castings constitute the most common form of alloy used in furnace design and should be used wherever possible, because in this form the alloy is most resistant to oxidation and warping in most cases, and because it is usually the cheapest form to make. If perfectly smooth surfaces are essential, alloy may be machined, but this should be avoided wherever possible, because of the high cost of machining this very hard material, and because machining increases the tendency to warp. For sections too difficult to cast, rolled forms may be used, and in occasional cases forgings are found to be best suited to the conditions to be met.

Cast or rolled alloy parts may be annealed by heating to a temperature recommended by the manufacturer, usually about 1650 deg. Fahr., followed by a thorough soaking at this temperature to remove casting and machining strains. This treatment is very desirable for all parts that are of such a shape as to warp readily, and in applications where very little warping is permissible. An example would be the small shafts used in forming the hearths of small roller-hearth furnaces.

A good example of the possibilities in the combining of different forms of alloy in the construction of a single part is a recent development in the design of carburizing boxes, where a web frame is made of cast alloy for strength and lined with light alloy sheet. This arrangement allows more rapid penetration of heat into the box, and should reduce the net fuel con-

sumption, because the box is lighter and carries less sensible heat out of the furnace.

Most alloys cannot be satisfactorily cut by means of an oxy-acetylene torch on account of their resistance to oxidation, but they can be readily welded with a special welding rod, a little experience, and particular care not to overheat the metal.

After the form of alloy best suited for the conditions has been selected, the nature of the stresses to which it will be subjected should be studied, and the size necessary safely to withstand these stresses determined. Most stationary alloy parts are required to withstand stresses which cannot be readily calculated, so that much of their design requires experience alone; but mechanism parts are usually more accurately determinable. The stresses are usually either bending or tensile stresses and can be calculated by the usual formulas, using values for strength which correspond to the furnace temperature. Several examples will illustrate this method.

Suppose that it is desired to determine the weight which a $\frac{3}{4}$-in. hexagon-section alloy rod will support at the center of a span of 24 in. at a temperature of 1800 deg. Fahr. From Fig. 79*b*, the formula for the maximum bending moment is $\frac{Wl}{4}$, where W is the weight at the center in pounds and l is the span in inches. The section modulus required equals the moment divided by the allowable fiber stress in pounds per square inch. Then:

$$\text{Moment} = \text{Modulus} \times \text{Fiber stress} = \frac{Wl}{4},$$

and

$$W = \frac{4 \times \text{Modulus} \times \text{Fiber stress}}{l}.$$

In the beginning of this chapter we saw that the allowable fiber stress for the average cast alloy is 500 lb. per sq. in. at 1800 deg. Since this is a rolled section, it will not be so strong as the cast form, and a fiber stress of 400 lb. per. sq. in. should be used. The section modulus of a hexagonal section is $0.54\ R^3$ where R

is the width of the flat, so that the modulus in this case will be 0.045 cu. in. Substituting:

$$W = \frac{0.045 \times 4 \times 400}{24} = 3.0 \text{ lb.},$$

the maximum weight which the bar will safely support at its center. These figures apply only for alloys of recognized worth at these temperatures. There is a great difference in the strength of alloys and other metals at high temperatures when the load is applied for a short time and when it is applied continuously for a long period, because the strength failure of metals under heat is a gradual process. A bar of the above size and made from good alloy should not deflect under a load much greater than that calculated, if the load is applied for only a short period, but it could not be counted on to support a weight in excess of 3 lb. for any great length of time.

As another example, suppose that it is desired to determine the size of side bars on an alloy chain to withstand a pull of 1000 lb. at a temperature of 1500 deg. Fahr. From Fig. 76, a safe figure for the ultimate strength of alloy in tension at 1500 deg. Fahr. is about 20,000 lb. per sq. in. On account of the great shocks to which any conveyor chain under heat is subjected because of the slipping and climbing of the chain on the sprockets when expansion takes place, a factor of safety of at least 15 should be used. The area required will then be:

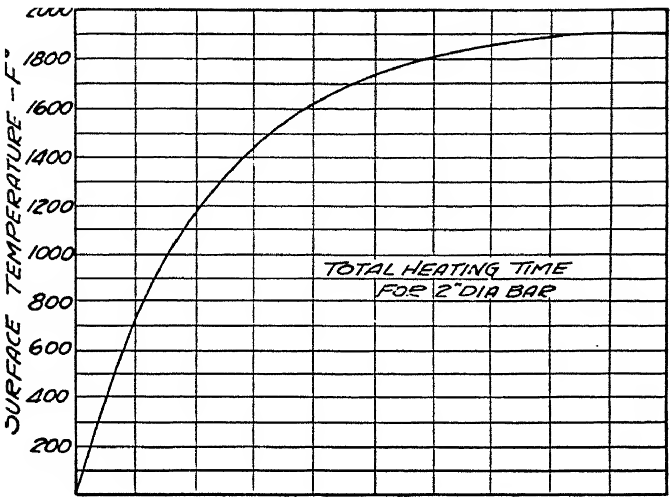
$$\frac{1000 \times 15}{20{,}000} = 0.75 \text{ sq. in.}$$

The consideration of the effect of expansion and contraction in alloy design is extremely important, because many of the cases of buckling of alloy parts are caused by neglect of this action. There is no permanent growth of alloy parts, but there is expansion, which must be allowed to take place freely if buckling and warping are to be avoided, because the strength of materials at high temperatures is not sufficient to withstand this force. Expansion and contraction will usually explain the cracking or warping of alloy parts, and frequently a small change

in the design of metal sections or provision for more uniform heating will eliminate the trouble.

Another consideration, which is important in the case of pusher bars or other members exposed at intervals to heat for short periods of time, is the rapidity with which metal parts become hot. This factor is considered in connection with oxidation rather than mechanical strength, and, consequently, only surface temperature is important. Parts that are exposed to heat at a temperature greater than 1600 deg. for more than three or four minutes should generally be made of alloy, because of the loss of strength and oxidation of other metals under these conditions; but when the period of exposure is less than about three minutes, there is no serious loss of strength, and the choice between alloy and cast iron or steel depends upon the size of the piece. A large section will heat more slowly on its surface than a small section and will frequently not reach an oxidizing temperature in short periods of exposure. In that case it is evidently unnecessary to make the part from expensive alloy. The exact determination of surface temperature for different sizes of parts and periods of exposure is a complicated matter, but a good idea of the rate of surface heating may be had from the curves of Fig. 82, which were calculated[1] to show the surface temperatures reached by cylindrical sections when exposed to a temperature of 2200 deg. Fahr. for various short periods. From these curves, it is evident that a pusher ram or other cylindrical member may remain in a high-temperature furnace without excessive heating for a period of at least three minutes if the section is 1 in. in diameter, and for a longer time if the section is greater. The rate of cooling outside the furnace may also be calculated, but this is usually unnecessary, because the cooling can be accelerated by a water spray. The initial rate of surface cooling in air from a temperature of 1900 deg. Fahr. is about 90 deg. per minute in the first few minutes of cooling of a 3-in. diameter round bar, and the variation with diameter is such that a 10-in. diameter cylinder cools in air at

[1] For method of calculation used, see *Fuels and Furnaces*, August, 1925, F. C. Andresen and Associates, Pittsburgh, Pa., publishers.



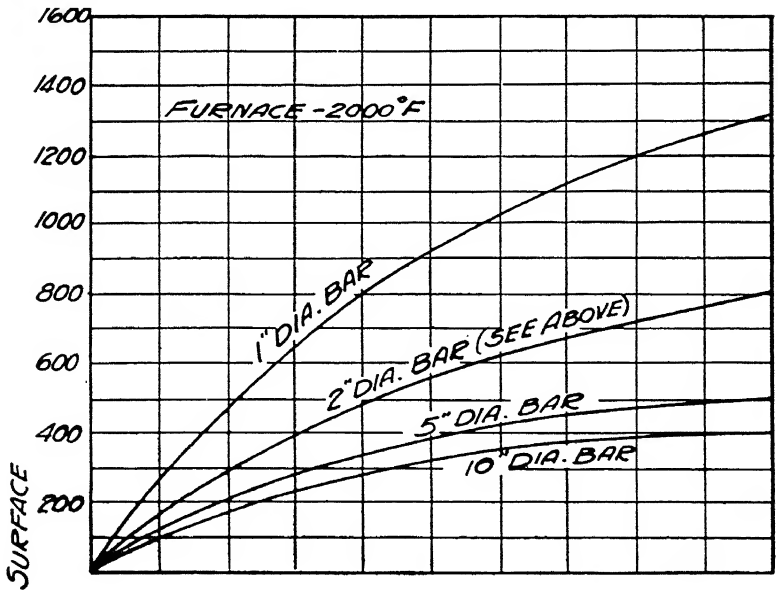


FIG. 82.—Surface Heating of Metal Bars.

the rate of about 50. deg. per minute in the first few minutes of cooling from a temperature of 1900 deg.

Water-cooled Parts.—The common use of water for cooling is in the skid pipes of continuous furnaces in which the temperature is too high to allow the use of alloy rails; but there are many other uses, such as the water pipes in the transverse skewbacks between longitudinal arches of the Morgan continuous billet-heating furnace, and the pipes imbedded in slotted furnace hearths to protect machinery located beneath these hearths. The use of water is seldom necessary in furnaces with a working temperature below 1900 deg. Fahr., and it should not be used except where absolutely necessary because of the heat which it carries out of the furnace.

Water-cooled castings, such as doors and skewbacks, are frequently used in open-hearth furnaces, but in heating furnace design the use of water is usually limited to cooling pipes and skid pipes. Skid pipes are either carried on piers to allow the hot gases of the furnace to pass below the heating material, or they are partially imbedded in the solid furnace hearth. In either case, the heating material must pass on to a soaking hearth of refractory before being discharged from the furnace, so that heat can flow into the cold spots where the metal has been in contact with the cold skid pipes. The pipes are usually carried down through the hearth and connected to a manifold running across beneath the furnace hearth, as shown in Fig. 33 of Chapter IV.

Care must always be taken that the skids are entirely full of water to prevent burning out, and to accomplish this the inlet is usually located at the lowest point of the skid and the outlet at the highest point. The outlet is arranged to discharge into a funnel in such a way that the flow of water is visible at all times and should be fitted with a controlling valve. The amount of water which will flow through a skid pipe or cooling pipe may be determined by the common hydraulic formula:

$$= 53 \quad Pd^5$$

where Q is the gallons flowing per minute, P is the water pressure in pounds per square inch, d is the internal diameter of the pipe in inches, and L is the length of the pipe in feet. To allow for bends and fittings, add 10 diameters to the pipe length for each rounded bend, 30 diameters for each 90-deg. elbow, and 60 diameters for each tee. To allow for rusting inside the pipe, reduce the flow calculated from the formula by 20 per cent.

As an example, in Chapter V the heat lost to a $2\frac{1}{2}$-in. double extra heavy skid pipe 40 ft. long was found to be 1,810,000 B.t.u. per hour. With an allowable temperature rise of 120 deg. in the water, the quantity required per minute will be:

$$\frac{1{,}810{,}000}{60 \text{ min.} \times 120 \text{ deg.} \times 8.35 \text{ lb./gal.}} = 30.1 \text{ gal. of water/min.}$$

To find the capacity of this pipe with 60 lb. per sq. in. water pressure:

$$53\sqrt{\frac{60 \times (1.77 \text{ in.})^5}{40}} \quad 270 \text{ gal./min.}$$

This indicates that, allowing the 20 per cent for rusting, the size of the pipe in this case is more than sufficient to pass the required quantity of water.

Auxiliary Furnace Equipment

Most furnace installations of any size include a considerable amount of auxiliary equipment, which includes door-raising mechanisms, pushers, fuel burners, and blowers for combustion air. Since many furnace troubles are caused by these auxiliaries, the practical designer or operator should be familiar with the principles of their design. The most important features of this equipment will constitute the remainder of this chapter.

Door-raising Mechanisms.—On the majority of small furnaces, the doors are raised by hand by means of a sway-bar (simple pivoted lever) arrangement, or by an endless chain around a large pocket sheave which is mounted on the shaft on which the sheaves for the door chains are fastened. On large furnaces, when the door is not frequently opened and when there is plenty

of time in which to open it, the latter arrangement is used with a train of gears included to reduce the force necessary on the chain. However, if the door is heavy and must be frequently opened, as is the case with many large furnaces, a hand arrangement is laborious, and some mechanical arrangement is employed, usually either an air cylinder or an electric hoist. The first is the ordinary air-cylinder hoist, and it will give excellent results if properly adjusted. If air is not available, or if close control of the door for varying heights and positions is desired, the electrical hoist is better, and there are many different and original arrangements. These vary from the direct use of a standard electric hoist to more complicated systems of levers, pinions, racks, and clutches, which are driven by motors through suitable gear reductions.

In determining the amount of power necessary, it is good practice to provide sufficient power to raise the dead weight of the door, in spite of the fact that the door is usually counterweighted. This counterweight, with mechanically raised doors, should be about 75 per cent of the weight of the door. If it is too small, unnecessary power is required to lift the door; if it is too large, the door will not stop quickly on rising and will not have sufficient effective weight to overcome the roughness in the guides when lowering. The speed of lifting is adjustable with an air hoist, but must be determined in advance for an electrical arrangement. This speed should not exceed 20 ft. per min.

The first cost of an electrical hoist is about five times that of an equivalent air hoist, and an idea of the comparative operating cost can be had from an example. Suppose that a door weighs 2400 lb. An air cylinder with that lifting capacity on 60 lb. per sq. in. air pressure will be 40 sq. in. in area (diameter 7 in. inside of cylinder). If the lift is 4 ft., the air required per stroke will be 1.11 cu. ft., which requires about 0.54 KW-hr. to compress to 60 lb. per sq. in. With an electric hoist the actual power used will be about:

$$25 \text{ per cent (net weight)} \times 2400 \text{ lb.} \times 20 \text{ ft./min.} = 12{,}000 \text{ ft.-lb./min.}$$

and, at an efficiency of 60 per cent for the hoist, the power required will be:

$$\frac{0.364}{0.60} = 0.60 \text{ KW-hr.}$$

Pushers.—There are many different kinds of pushers and each installation is different, but the principles are always alike. The first step in the design of a pusher is to determine the force necessary to move the material to be pushed. As mentioned in Chapter IV, the accepted practice is to base the design on a force equal to the dead weight of the material to be moved, which corresponds to a coefficient of friction of unity. This is not an excessive allowance, because tests conducted on pusher-type furnaces have indicated that the coefficient of friction is very frequently 0.50 to 0.60 and sometimes approaches unity in high-temperature furnaces where the hearth conditions are especially bad. The determination of motor power required to exert the necessary push depends upon the mechanical arrangement. The selection of the best mechanical arrangement from a study of the characteristics of different methods was discussed in Chapter IV, and the calculation of efficiencies at this point can best be shown by several examples.

In the bell crank lever pusher of Fig. 83 (see Fig. 33 in Chapter IV), suppose that 33 billets in the furnace are to be pushed a distance of 12 in., and that each billet weighs 427 lb. The push in this case will then be 14,100 lb. If arm *a* equals arm *b* in length, the diameter of the crank will be 12 in. for a 12-in. stroke and the maximum force at 90 deg. to the crank will equal the total push required. Then the torque will be 6 in. (radius) × 14,100 lb., or 84,600 in.-lb. Now assume that a complete stroke cycle is to be completed at the rate of five per minute. If the crank is driven through a spur-gear reducer, the formula for the horsepower to be delivered by the gears is:

$$\text{HP.} = \frac{T \times N}{63{,}025},$$

where T is the torque in inch-pounds and N is the revolutions per minute of the reduction gear. In this case,

$$\text{HP.} = \frac{84{,}600 \times 5}{63{,}025} = 6.71,$$

and if a 900 R.P.M. motor is used, the reduction required will be $\frac{900}{5}$ or 180 : 1. A standard spur-gear reduction rated at $7\frac{1}{2}$ HP. with a 175 : 1 reduction would be satisfactory. The efficiency of a spur-gear reduction is from 90 to 95 per cent, so that the

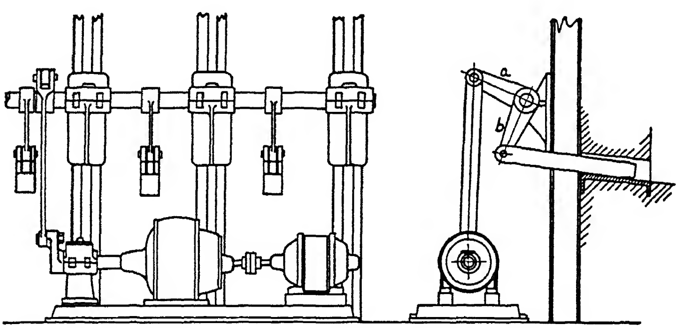


FIG. 83.—Bell Crank Lever Pusher.

driving motor power required is not much greater than the power to be delivered by the reduction gears, and a $7\frac{1}{2}$-HP. motor would be large enough in this case.

Now suppose that the pusher shown in Fig. 30 is required to push a load of 5000 lb. at a speed of 30 ft. per min. A rack with a diametral pitch of 2 and a face 4-in. wide will have ample strength, and a 6-in. diameter pinion with 12 teeth will be suitable for driving this rack. The R.P.M. of this pinion for a speed of 30 ft. per min. will be:

$$\frac{30 \text{ ft./min.} \times 12 \text{ in./ft.}}{6\pi \text{ (circumference)}} = 19.1,$$

and if a 1200 R.P.M. motor is used the reduction required will be 63 : 1. The torque on the pinion will be:

$$3 \text{ in. (radius)} \times 5{,}000 \text{ lb.} = 15{,}000 \text{ in.-lb.}$$

The formula for horsepower delivered by a worm-gear reducer is the same as was given in the preceding example for a spur-gear reducer, so that the horsepower of the reducer will be:

$$\frac{15{,}000 \times 19.1}{63{,}025} \quad 4.55.$$

A 63 : 1 worm-gear reducer with a rating of about 5 HP. will therefore be required. The efficiency of worm-gear reducers at slow speed is only about 60 per cent, so that a 10-HP. motor should be direct-connected to this reducer in order to have ample power available.

As a final example, suppose that a screw-type pusher is required to push a load of 25 tons in an ingot-heating furnace. A common arrangement of this type of pusher includes a stationary screw and a driven nut to which is fastened the pusher head. The nut is driven through a spur-gear reduction. Suppose that in this case the screw is 8-in. pitch diameter and has 3 threads to the inch. If the nut revolves at a rate of 180 R.P.M. to obtain a pusher speed of 5 ft. per min. ($\frac{1}{3} \times 180 = 60$ in./min.), the horsepower delivered by the screw will have to be:

$$\frac{25 \text{ tons} \times 2000 \text{ lb./ton} \times 5 \text{ ft./min.}}{33{,}000 \text{ ft.-lb./min. per HP.}} = 7.6 \text{ HP.}$$

The efficiency of a screw as adapted to a pusher of this kind is expressed by the formula:

$$e = \frac{\tan b}{\tan (b + a)} \quad \text{(Marks' \textit{Mechanical Engineers' Handbook})},$$

where b is the angle of inclination of the threads and a is the angle of friction.

$$\text{Angle } b = \tan^{-1}\frac{l}{2\pi r},$$

where l is the lead of the thread in inches and r is the radius of the screw. In this case:

$$b = \tan^{-1} \frac{}{\times 4} = 0.8 \text{ deg.}$$

Using a value of $a = 6.3$ deg. (average angle of friction),

$$e = \frac{\tan 0.8 \text{ deg.}}{\tan 7.1 \text{ deg.}} = 0.106.$$

Disregarding the friction in the bearings, the power delivered by the spur gear to the screw must be:

$$\frac{7.6}{0.106} = 71.5 \text{ HP.}$$

The efficiency of the spur gears will be about 95 per cent, so that the motor horsepower should be 75. With a single 5 : 1 ratio spur-gear reducer, a 900 R.P.M. slow-speed motor can be used. It is permissible to disregard bearing friction in the machine because of the selection of unity friction coefficient for this large load, where the safety factor is relatively greater than for small loads. The high motor horsepower obtained in the example is partly due to the selection of screw characteristics in this case. The angle of inclination of this thread is very small, with consequently low efficiency for the screw. Better results would have been obtained by using a bigger thread turning at slower speed. More reduction would have been required in the spur gearing, but the lower efficiency of more spur gears would have been more than offset by the increased efficiency of the screw. For instance, if a thread with a 1-in. pitch and the same diameter were used, the efficiency of the screw would be 26.3 per cent. The speed of the screw would be only 60 R.P.M. and a reduction of 15 : 1 would be required if a 900-R.P.M. motor were used. This would require two spur gears, and the horsepower required at the motor would be about:

$$\frac{7.6}{0.263 \text{ eff.} \times 0.95 \times 0.95} = 32 \text{ HP.}$$

The example was selected to illustrate the necessity for careful consideration of all of the factors involved in the design of this type of machinery.

These illustrations show the general method of solving problems of this sort. The principal necessity is to be sure that the machinery used in connection with furnaces is amply strong, as illustrated by the example of designing pushers with sufficient power actually to lift the load, so that the tremendous energy necessary to move hot material in a furnace will be available.

Oil and Gas Burners.—It is not within the scope of this discussion to consider in detail the design and construction of the many forms of burners, but there are some factors with which the furnace designer or operator should be familiar. Many furnace difficulties originate at the burners, and most of them can be readily overcome if the operation of the burners is understood. The function of most burners is to atomize or finely divide the fuel and to mix it with the combustion air. The method of calculating the probable amounts of fuel and air required has been discussed in previous chapters, but the actual measurement of these quantities is frequently impossible because of lack of the necessary apparatus. The failure of a furnace to heat properly is very often due to lack of capacity in the burners, and their capacity is limited by the amount of combustion air which they will pass. A rapid and effective check of this feature of a burner may be made without actual measurement if the air pressure and orifice size are known. The air pressure can be determined by means of a simple U-tube manometer, and the outlet size of the burner can be measured.

Table 25 shows the capacity, in cubic feet per hour, of thin orifices for different pressures. These orifices are similar to the openings found in most forms of gas burners. Table 26 gives the amount of air which will pass through the openings found in most oil burners for different air pressures. (Figure 84 shows opening in a typical low-pressure oil burner.)

The formula from which the values of Table 26 were calculated is:

$$Q = 27.6$$

TABLE 25

CAPACITY, IN CUBIC FEET PER HOUR, OF THIN ORIFICES SIMILAR TO OPENINGS IN GAS BURNERS *

Ounces per Square Inch	Tenths of Water	Tenths of Mercury	Diameter, Inches						
			$\frac{5}{64}$	$\frac{3}{32}$	$\frac{7}{64}$	$\frac{1}{8}$	$\frac{5}{32}$	$\frac{3}{16}$	$\frac{1}{4}$
0.12	2.0	0.15	4	6	8	10	16	22	40
0.23	4.0	0.29	6	8	12	15	23	34	60
0.35	6.0	0.44	7	10	14	18	28	40	76
0.46	8.0	0.59	8	12	16	21	33	47	84
0.58	10.0	0.73	9	13	18	23	36	52	92
0.69	12.0	0.88	10	14	19	25	39	56	100
0.79	13.7	1.00	11	15	21	27	42	61	108
0.81	14.0	1.04	11	15	21	27	42	61	108
0.92	16.0	1.19	11	15	22	29	47	67	120
1.04	18.0	1.33	12	17	24	31	48	69	124
1.15	20.0	1.47	13	18	25	33	51	74	132
1.44	25.0	1.83	14	20	28	36	56	81	144
1.58	27.3	2.00	15	21	29	38	59	85	152
2.00	35.6	2.61	17	24	33	43	67	97	172
2.38	40.9	3.00	18	26	36	47	73	106	188
3.16	54.6	4.00	21	30	42	54	84	121	216
3.95	68.2	5.00	23	34	46	60	94	135	240
4.73	81.9	6.00	26	37	51	66	103	148	264
5.52	95.5	7.00	28	40	55	71	111	160	284
6.31	109.2	8.00	30	43	59	76	119	171	304
7.10	122.8	9.00	31	45	61	80	125	180	320
7.89	136.5	10.00	33	48	65	85	133	191	340
8.68	150.1	11.00	35	50	69	89	139	200	356
9.46	163.7	12.00	36	52	72	93	145	209	372
10.25	177.4	13.00	38	55	75	98	153	220	392
11.04	191.1	14.00	39	57	78	101	158	227	404
11.83	204.7	15.00	41	58	80	104	162	234	416
12.62	218.3	16.00	42	60	83	108	168	243	432
13.41	232.0	17.00	43	62	85	111	173	250	444
14.20	245.6	18.00	44	64	88	114	178	256	456
14.99	259.3	19.00	46	66	90	117	183	263	468
15.78	273.0	20.00	48	68	93	121	189	272	484

* Based upon data furnished by the Metric Metal Works.

TABLE 26

CAPACITY OF OIL-BURNER OPENINGS IN CUBIC FEET OF FREE AIR PER MINUTE *

Orifice Diameter, Inches	Air Pressure, Ounces per Square Inch				
	8	12	16	20	24
$\frac{1}{2}$	15.0	18.8	21.0	24.0	26.3
$\frac{3}{4}$	34.5	42.0	48.8	54.0	60.0
1	61.5	75.0	86.3	96.0	106.0
$1\frac{1}{4}$	96.0	116.0	135.0	151.0	165.0
$1\frac{1}{2}$	137.0	165.0	193.0	216.0	236.0
$1\frac{3}{4}$	188.0	227.0	262.0	292.0	322.0
2	244.0	296.0	343.0	382.0	420.0
$2\frac{1}{4}$	307.0	375.0	431.0		
$2\frac{1}{2}$	382.0				

* Based upon data furnished by the Ingersoll-Rand Company.

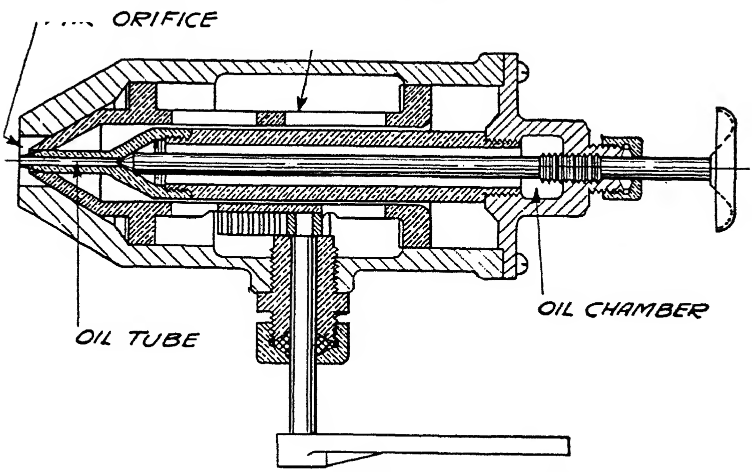


FIG. 84.—One Form of Low-pressure Oil Burner in Closed Position—Air and Oil Enter Burner through Connections on under Side.

where A is the area of the orifice in square inches, C is a coefficient (0.75 used in this case), and H is the pressure in inches of water column.

For high-pressure burners, the relation of capacity of air to orifice size and pressure can be seen in Table 27.

TABLE 27

CAPACITY OF HIGH-PRESSURE ORIFICES IN CUBIC FEET OF FREE AIR PER MINUTE

(Orifices are considered to be slightly rounded on inside, as in most oil burners. For sharp, square entrances, multiply the values by 0.70).

Orifice Diameter, Inches	Air Pressure, Pounds per Square Inch							
	30	40	50	60	70	80	90	100
$\frac{1}{16}$	2.5	3.0	3.7	4.2	4.8	5.3	5.9	6.4
$\frac{5}{64}$	4.0	4.8	5.7	6.6	7.4	8.3	9.2	10.1
$\frac{3}{32}$	5.7	6.9	8.1	9.4	10.7	12.0	13.2	14.5
$\frac{7}{64}$	7.7	9.3	11.0	12.7	14.4	16.1	17.9	19.6
$\frac{1}{8}$	10.0	12.2	14.5	16.8	19.0	21.2	23.5	25.8
$\frac{1}{4}$	40.0	49.1	58.2	67.0	76.0	85.0	94.0	103.0
$\frac{3}{8}$	90.0	110.5	130.0	151.0	171.0	191.0	211.0	231.0
$\frac{1}{2}$	161.0	196.0	232.0	268.0	304.0	340.0	376.0	412.0
$\frac{5}{8}$	252.0	307.0	364.0	420.0	476.0	532.0	587.0	645.0
$\frac{3}{4}$	362.0	442.0	522.0	604.0	685.0	765.0	843.0	925.0

In using these tables to check the fuel capacity of burners, it must be remembered that, in many burners, only part of the combustion air is supplied under pressure with the fuel, the remainder being induced or inspirated from the atmosphere. Most oil burners induce about 40 per cent of the necessary air when operating on air at 8 oz. per sq. in. pressure; 50 per cent with 16 oz. pressure; 60 per cent with 24 oz.; 90 per cent with 45 lb. in high-pressure burners; and 92 per cent with 90 lb.

As an example of the method of checking burner capacity, suppose that a burner is designed for operation on 8 oz. per sq. in. air pressure and has an orifice which is $1\frac{1}{2}$ in. in diameter. Actual measurement of the air pressure shows that it is 8 oz. (13.8 in. of water) with the air line to the burner wide open. Then, from

Table 26, the capacity of the orifice will be 137 cu. ft. of free air per minute. (The oil content of the oil-air mixture through the orifice is neglected.) The percentage of induced air will be about 40, so that 60 per cent must be supplied through the burner. If the amount of air required per gallon of oil is 1410 (see Table 2) plus 10 per cent × 1410, or a total, including excess air, of 1551 cu. ft. per gal., the capacity of the burner will be:

$$\frac{137 \times 60 \text{ min./hour}}{60 \text{ per cent} \times 1551} = 8.83 \text{ gal. of oil/hour.}$$

A simple calculation of this kind will frequently disclose the evident reason why a furnace will not get as hot as is desired.

The size of oil tubes in oil burners is always larger than is necessary, so that the tubes seldom limit the capacity. The capacity of small oil tubes, however, is occasionally of interest, and Figs. 85 and 86 are given to show actually measured capacities of two sizes of small brass tubes. The tests were made with 28–30 Bé. gravity oil at 70 deg. Fahr., and the illustration show the capacities in gallons of oil per hour for various pressures and lengths.

Piping.—In arranging the piping for fuel and air to furnace burners, it is usual to employ a connection pipe of the same size as the connection on the burner. Where this pipe must be very long, or where several burners are to be connected into a manifold pipe, it is frequently desirable to calculate the pressure drop, in order to be sure that the pressure drop between the supply and the burners is not sufficient to cause an insufficient pressure at the burners. This is clearly brought out in the gas burner example of Chapter IX, and it is just as important in the case of air supply to oil burners.

The flow of air and gases in pipes can be checked by the formula:

$$h = \frac{Q^2 sL}{1323 D^5},$$

where h is the pressure drop in inches of water, L is the length

of the pipe in feet, Q is the quantity of air or gas flowing in cubic feet per minute, s is the specific gravity of the gas (air = 1.0),

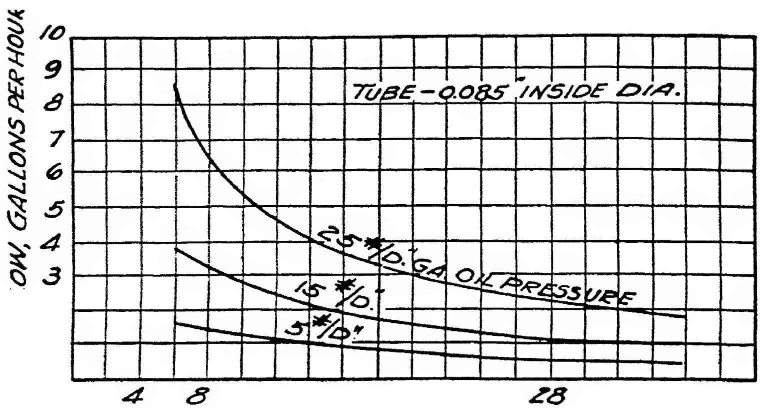


FIG. 85.—Flow of Oil in Small Tube.

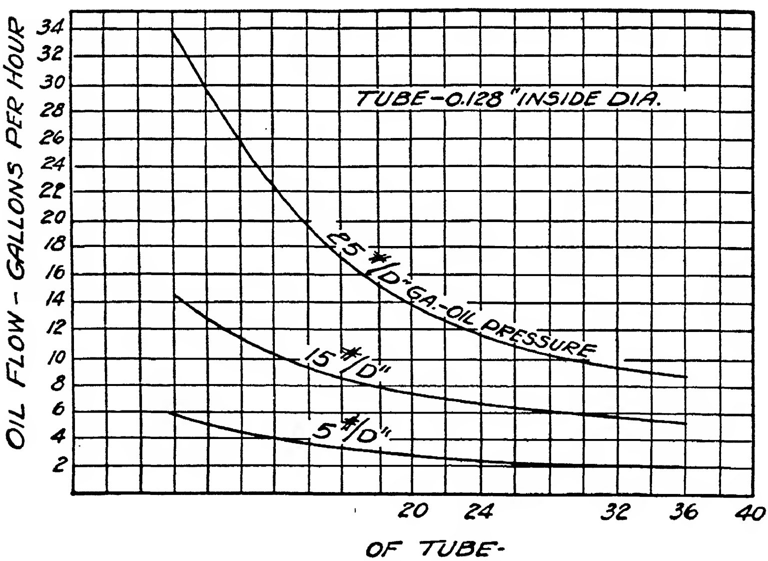


FIG. 86.—Flow of Oil in Small Tube.

and D is the diameter of the pipe in inches. Elbows in the line can be allowed for by adding as follows:

Number of pipe diameters in elbow radius...	½	1	2	5
Equivalent feet of straight pipe............	121	17.5	9	7.8

The friction loss in oil lines is usually unimportant, because of the difference between the pressure supplied by the pump (up to 100 lb. per sq. in.) and the desirable pressure at the burner (8 to 10 lb. per sq. in. desirable in most burners to reduce the possibility of clogging of the needle valve). However, in the case of long lines or where a large oil-burning system is to be installed, it is frequently desirable to determine the friction loss. The pressure drop in oil lines may be calculated from the formula:

$$Q^2$$

where P is the pressure drop in pounds per square inch, L is the pipe length in feet, D is the pipe diameter in inches, s is the specific gravity of the oil referred to water, Q is the gallons of oil flowing per minute, and f is the friction coefficient. Values of the friction coefficient, worked out by Mr. J. D. Keller at the Carnegie Institute of Technology, are as follows (see Chapter II for viscosities of oil):

$\dfrac{\text{Gallons per Min.} \times \text{Specific Gravity}}{\text{Pipe Diameter, In.} \times \text{Saybolt Viscosity}}$	$1000 \times f$
0.01	6.0
0.02	3.0
0.05	1.1
0.10	0.56
0.20	0.70
0.40	0.56
1.0	0.44
10.0	0.27
20.0	0.25
60.0	0.22

Elbows may be allowed for by adding 25 pipe diameters for each 90-deg. elbow.

Miscellaneous Items.—Low-pressure oil and gas burners require some type of fan or blower. The two most common types are the positive-pressure fan, or turbo-compressor, and the constant-volume blower. Each of these types will deliver air satisfactorily to the burner, but each has its peculiar advantages and disadvantages. The constant-volume blower is inexpensive, but if the demand is reduced the pressure will build up to as much as 10 or 15 lb. per sq. in. and the motor will overheat. This type must, therefore, have a suitable relief valve or hand control, and large quantities of air must frequently be wasted when it is not required at the burner. Constant-pressure blowers are more expensive, but so long as the demand does not exceed the capacity of the blower, the pressure will not vary greatly because it is independent of the quantity of air being used.

Piping from blowers to burners can consist of either standard metal pipe or sheet-iron pipe, and should contain slide-damper blast gates in place of valves for regulation, as the former give less friction loss and quicker regulation. These gates should be far enough away from the burner to permit the air to expand and eliminate excessive velocity and turbulence when entering the burner. This distance is about 18 in. from the burner. A large blast gate should always be installed at the blower.

Lighting Furnace Burners.—It seems appropriate at this point to consider briefly the lighting of furnace burners, a knowledge of which is of assistance in putting a furnace installation into satisfactory operation.

Assuming that the burner equipment and piping have been completed and that the brickwork of the furnace has been arranged according to the proper principles, the final step is the lighting of the furnace. This is not so easy as it appears in most cases, and without some knowledge of the fundamentals of operation the first experience can be decidedly unpleasant.

The chief source of trouble in lighting a cold furnace is the effect of cold surfaces upon combustion. When a mixture of atomized oil and air is ignited and fired into a cold furnace

against cold brick and metal surfaces, the temperature of the products of combustion is suddenly reduced. As a result, a large percentage of the finely divided carbon particles which have not yet had an opportunity to burn are cooled below the ignition temperature and form dense smoke, or are deposited in the form of soot on the cold surfaces. The difficulty is more pronounced in the case of oil than of gas, because the particles are larger and more difficult to burn rapidly. As the brick surfaces become hotter, they offer increasing assistance in vaporizing the oil, and the only great difficulty experienced is in keeping the burner lighted until the refractories become heated.

The following procedure should be followed in lighting oil and gas burners: After placing a lighted ball of waste, saturated with carbon oil, close to the mouth of the burner:

First.—Turn on a slight amount of atomizing air or steam, just sufficient for the ignition of a slight amount of fuel.

Second.—Allow a slight amount of fuel to enter the furnace, so that a small but steady flame is obtained.

Third.—Increase the air, and then the fuel, a little at a time, until the maximum amount of fuel which will burn steadily in the cold chamber is reached. Allow the burner to operate at this point until the bricks become hot, and then gradually increase the air and fuel as fast as the temperature of the bricks will sustain ignition, until the full temperature required is reached.

Fourth.—Adjust the oil to the required amount, then increase the air supply until smoking just disappears; finally, decrease the air slightly to insure against excess air and oxidizing conditions in the furnace.

In most oil burners, atomization is accomplished by air under pressure, and the mixed oil and air leave the burner with a velocity which is greater than the speed of ignition of the mixture when not assisted by the vaporizing effect of hot surfaces. For this reason, it is always advisable to place a brick or other baffle in front of an oil burner, at least while lighting, in order to break up the velocity and afford the air and oil mixture an opportunity to light before passing through the furnace

chamber. This arrangement also tends to confine the greatest heat to the brickwork near the burner, causing it to heat up faster and accelerate combustion, as explained above. If it is not easy to arrange a brick in front of the burner, a sheet-metal shield can be inserted through the burner hole and arranged so as to be partially in the path of the mixture from the burner. This shield can be removed when the burner is lighted.

It should be remembered in starting an oil burner that unburned combustion gases constitute an extremely effective fire extinguisher, so that if too much oil is turned on at first the furnace will be filled with cold smoke and the flame will be smothered. When this happens, as it almost invariably will at first, the oil should be shut off and the air or steam allowed to blow the gases out of the furnace before another attempt is made to light the burner. In this connection, it should also be remembered that the oil-saturated torch is also producing smoke, so that for small furnaces it is best to keep this torch small enough to prevent filling the chamber full of smoke before the burner is turned on.

The danger of any serious explosion when lighting an oil burner is not so great as with gas, but some danger is present and care should be used. For that reason, never turn on the oil first, because it will collect in the furnace, and when sufficient air has been admitted an explosion may result. If, however, the air is turned on first so that there is plenty of air available, the oil will ignite as it is admitted. The doors of a furnace *should always be open when the furnace is lighted*, to prevent any serious result from the rapid expansion of gases when slight explosions occur.

Before lighting up a green furnace which has just been completed, it should be thoroughly dried out by means of a wood, coal, or gas fire at low temperature. This removes the moisture in the brick and clay and prevents cracking of the brickwork when it is heated to high temperatures. For large furnaces, this process should last for several days, and in all cases it should be continued until steam and moisture are no longer given off by the brickwork.

This completes the general discussion of the practical points in connection with the design of metal furnace parts, and we are now ready to conclude the consideration of the practical aspects of furnace design with a consideration of the methods of furnace control in the next chapter.

CHAPTER V

TEMPERATURE MEASUREMENT AND FURNACE CONTROL

THE preceding chapters have been devoted to the selection of fuels and furnace types, and to the design of the principal parts of the average furnace. It remains now to consider the means for determining the temperature in the furnace and for controlling the temperature, atmosphere, and pressure so as to secure and maintain the most desirable combination of these factors.

The desirability of accurately controlling the conditions in a furnace is being increasingly appreciated, and the realization that fuel economy, long furnace life, and minimum wastage of heated material can be assured only by constant knowledge and control of the conditions prevailing is steadily spreading over the entire heating field. Considering only industrial furnaces, the field includes the hardening, annealing, drawing, and other heat treatment of various metals, glass making, cement manufacture, chemical processes, and enameling, and it can be readily realized what a tremendous total of economy can be effected through the proper operation of all the furnace equipment included in these industries.

The three fundamental factors which affect the operation of a furnace are temperature, atmosphere, and pressure. The first of these has received the widest attention, and instruments designed for its control have had the greatest development and the widest application to heating equipment. In the consideration of the phenomenon of temperature, it must be understood that temperature is not a measure of heat input, but is a function of both heat input and heat requirements of the furnace and charge. Less heat (in B.t.u. or Calories) is needed to maintain

a given temperature (in degrees Fahrenheit or Centigrade) in a small furnace than to maintain the same temperature in a large furnace, because the capacity for absorbing and losing heat is smaller in the smaller furnace. Again, when a cold charge is introduced into a hot furnace, the temperature drops, although the rate of heat input remains the same. The suddenness of this drop is controlled by the *flywheel* action of sensible (contained) heat stored in the furnace refractories, as will be seen later. Webster vaguely defines temperature as "the condition of a body with respect to sensible heat." An analogy to help explain heat and temperature is a liquid storage tank, where the inlet flow corresponds to heat input, the amount withdrawn from the tank to heat required, the amount of liquid in the tank to sensible heat, and the height of liquid in the tank to temperature.

The factor of furnace atmosphere is a chemical consideration, and refers to the composition of the gases resulting from the combustion of the fuel. When a fuel is perfectly burned, every particle of its combustible content is oxidized by combustion air and every particle of air is utilized, so that neither unburned combustible or excess air remains. Such perfection is not possible in practice, but the proportioning of fuel to air to obtain the nearest possible approach to this condition is the purpose of atmospheric control apparatus.

The last factor, furnace pressure, is frequently neglected. It depends upon the amount of combustion gases generated in the furnace and the size and location of the openings through which they may escape. If they may escape too easily a vacuum is created in the furnace and excess air is drawn in to oxidize the heating material, while if the openings are too small an excess pressure is created which forces flame out through doors and seals. If the vents are not properly located both vacuum and pressure may exist in the same furnace chamber.

The complication of the design of temperature and atmosphere control apparatus is increased by the existence of fuel in the forms of solids, liquids, and gases. The physical characteristics, methods of handling, and processes of combustion are so

entirely different for the different kinds of fuels that a wide variation of appratus is necessary. All of it is based upon the same principles of constantly proper proportions of heat input to heat required for temperature control, and of combustible fuel content to combustion air for atmosphere control, but the methods of realizing these conditions are widely different. The control of furnace pressure is the only factor that is independent of the fuel used, since it depends on the gases produced from combustion, which are the same for all forms of fuel.

Before considering the details of different types of controls, let us see the essential parts of each type and have a clear understanding of the differences between the three types for control of temperature, atmosphere, and pressure.

The starting point for the control of temperature is the measurement of temperature, the science and practice of which is especially important because most furnace equipment includes means for measuring temperature, whether it is arranged to control it automatically or not. Instruments for temperature measurement are either indicating (when the temperature is simply indicated at any time, usually by means of a pointer and dial or scale), recording (when the temperature is continuously marked on a paper chart to make a permanent record), controlling (when provided with adjustable contacts to open and close at predetermined temperatures), or any multiple combination of these three types. In automatic control equipment, the contacts of the controlling instrument are usually part of a very low-voltage circuit which actuates a relay to control the circuit of greater voltage that operates the control apparatus proper. This latter apparatus varies the supply of fuel or heat energy to the furnace, as will be seen later.

When the supply of fuel to a furnace is varied by hand, the supply of combustion air may either be varied by hand also, or it may be automatically maintained in the correct proportion to the fuel by atmosphere-control apparatus. When the supply of fuel is varied by automatic temperature control, the supply of air must either be simultaneously controlled by the temperature controller or an atmosphere controller must be used to keep

the air in proportion to the fuel. This distinction between automatic temperature control and automatic atmosphere control is somewhat confusing, and the following list reviews all of the possibilities:

1. Hand control of both fuel and air.
2. Hand control of fuel and automatic control of air by atmosphere controller.
3. Simultaneous control of fuel and air by temperature controller.
4. Control of fuel only by temperature controller and automatic control of air by atmosphere controller.
5. The second and fourth of the above may be reversed so that the flow of air regulates the flow of fuel.

An atmosphere controller is an instrument which utilizes some physical principle to make the flow of solid, liquid, or gaseous fuel regulate the flow of air so that it will always be in the same proportion, or, in some cases, to make the flow of air regulate the fuel. Automatic pressure-control apparatus consists of a means for measuring pressure in a furnace and, by means of contacts, actuating a relay circuit when this pressure rises or falls to a predetermined value. This relay circuit controls the actuating circuit which operates the mechanism required to close or open a flue-gas damper.

Temperature Measurement

The increase in the importance of temperature measurement has been very rapid in recent years, largely because of advances that have been made in the science of heat treating. As the amount of precision machinery, such as automobiles, typewriters, tools, and countless other things that are taken for granted in our modern life has increased, the heat treater has had to devise more accurate means of obtaining varying metal characteristics, and the first necessity is accurate temperature control. Also, as factories and mills have increased in size and complication, it has become necessary to keep records of the history of each product

through the course of its manufacture in order that the causes of good or bad qualities in the finished product may be traced through the various steps in its making.

These principal incentives have resulted in scientific instruments for the reliable measurement and recording of furnace temperatures. Dependence upon the eye of a man with long training and experience in heat treatment is no longer within the limits of accuracy found to be essential, and the use of the old-fashioned water calorimeter, operated by plunging a hot silver ball of known weight into a known quantity of water and measuring the temperature rise, is too slow and cumbersome for adequate control and leaves no record behind it for useful reference.

Although, as is usually the case, the incentives for better temperature measurement resulted from the demands for better product, the use of better pyrometers has also improved the operation of industrial furnaces and increased the opportunities for more accurate design of furnaces, by the collection of reliable data on the performance of furnace-building materials. Some of the benefits to furnace operation resulting from the use of temperature-measuring devices are greater fuel economy, reduction of heating time by elimination of the margin of safety necessary with the old methods, reduction of labor, longer furnace life by elimination of unnecessarily high temperatures in the furnace, greater temperature uniformity by affording means of checking temperatures at various points in the furnace, and higher morale of furnace attendants. All of these advantages are of great benefit to the furnace designer.

Most pyrometers belong to one of four general classes: thermoelectric, low-temperature, radiation, and optical. The thermoelectric type is based on the fact that when two wires of different materials are heated in contact with each other, a very small electric current is produced in these wires, the amount of which has a fixed relation to the temperature of the junction of the two materials. Low-temperature pyrometers are usually of the expansion or the resistance types. The expansion type depends upon the constant relation between the expansion of gas

or of a solid rod when heated and the temperature to which it is heated. For the resistance pyrometer, the relation between the temperature of a coil of wire of certain material and its corresponding electrical resistance is utilized. The radiation variety has no parts in the furnace heat and is based on the measurement of the heat emitted by black-body radiation through an opening in the furnace wall. The optical pyrometer is also entirely outside of the furnace and depends upon the measurement of the amount of light given off by a hot furnace or body.

Before considering each of these types in more detail, it is important to understand some of the factors which affect the principles of operation of these instruments. The purpose of most furnace-temperature measurements is to measure (1) the temperature of the furnace gases, (2) the temperature of the furnace walls, or (3) the temperature of the heated material. In the usual furnace operation these values are not the same, and considerable confusion results from failure to keep them separate in considerations of temperature measurement.

The distribution of temperature in furnace gases varies with the design of the furnace. For instance, in direct-fired furnaces, the flames of combustion are developed in the heating chamber. If the furnace is properly designed, these flames do not strike the heating material directly, but are cooled by radiation and convection to the furnace walls and by radiation to the material, so that by the time the gases come in actual contact with the material they are at the average temperature of the furnace. A measurement of the actual flame is therefore much higher than the average furnace temperature, and such measurements are the greatest cause of confusing results. *Thermocouples should never be located in the direct path of a burner.* As a general rule, thermocouples (the hot junction of thermo-electric pyrometers) should be located near the heating material, away from any point where they might be cooled by possible infiltration of cold air, and out of the way of material handled in and out of the furnace. In continuous furnaces, they are located close to the discharge point of the material, as the temperature of the material as it leaves the furnace is the most important in most heat-

ing processes. Figure 87 illustrates good and bad locations for the thermocouples in several common applications.

The measurement of actual wall temperatures is different from that of the gases and is difficult unless a pyrometer couple is inserted through the wall from the outside to a point within about $\frac{1}{8}$ in. from the inside face. Radiation and optical pyrometers are effective for wall-temperature measurements if the atmosphere of the furnace is fairly clear, otherwise they measure the temperature of the gases.

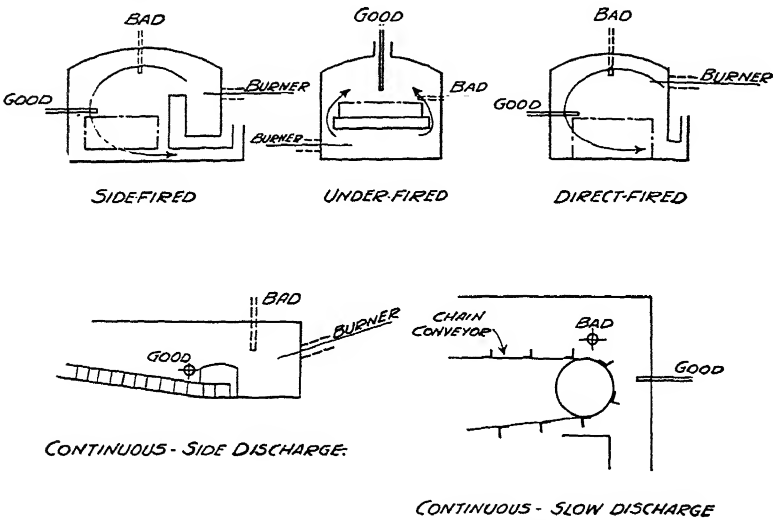


FIG. 87.—Location of Thermo-couples.

Much the same difficulty applies to the measurement of actual material temperature as to wall temperature. If the heated material is in piles on the furnace, good results are obtained from thermocouples inserted into the center of the pile where it is protected from the sweep of the furnace gases. In the determination of temperature of material after it has been taken out of the furnace, care must be taken because the iron oxide (scale) covering the material cools very much faster than the metal itself. This scale must be knocked off the metal before its temperature is measured, and many erroneous data have resulted from neglect of this precaution.

Let us now consider in more detail the four classes of pyrometers:

Thermo-electric Pyrometers.—These instruments always consist of two parts: the hot junction, located in the heat; and the instrument for measuring and recording, in terms of temperature, the current produced in heating this junction. The materials used for the two wires of the thermocouple, and for the protecting tube surrounding the couple, vary with the temperature. The following are some of the combinations, with temperature limitations specified by the manufacturers:

Thermocouple Metals	Protecting Tube	Maximum Temperature, Deg. Fahr.
Iron—Constantan	None	800
Copper—Constantan	None	800
Iron—Constantan	Wrought iron	1500
Nickel chromium—Constantan	Calorized iron	1600
Iron—Constantan	Calorized iron	1700
Nickel chromium—Nickel aluminum	None	1800
Chromel—Alumel	Nichrome	2000
Platinum—Platinum rhodium	Nichrome	2200
Platinum—Platinum rhodium	Porcelain inside and firebrick outside	2900

In some cases where iron is used as the positive metal of the couple, the tube itself replaces the iron wire, but in all cases the two metals are carefully insulated by porcelain insulators at all points except the junction at the furnace end of the couple, and the length of the couple has no effect on its operation. The protecting tubes are used to protect the wires from oxidation and the corrosive action of gases when the thermocouple is installed permanently, but are frequently eliminated in temperature tests of short duration. These tubes must have a high thermal conductivity and must be sensitive to changes in temperature, to avoid lags in the temperature readings.

The instruments for measuring the electrical force set up in the

thermocouple are usually of either the *potentiometer* type or the *millivoltmeter* type. The principle of the potentiometer type is that of the well-known Wheatstone bridge. This electrical arrangement comprises two interconnected circuits. The thermocouple circuit includes the thermocouple and a galvanometer. The potentiometer circuit includes a standard source of constant current and a variable resistance. These two circuits are opposed in such a manner that the resistance in the potentiometer circuit can be varied so that the unknown current in the thermocouple circuit is exactly offset, and the galvanometer will point to zero. The variable resistance is made in the form of a slidewire, and the linear movement of the slide, as it keeps the galvanometer at zero, is calibrated to read the temperature directly in degrees. The other type of instrument, called the millivoltmeter type, measures the extremely small E.M.F. of the thermocouple directly by means of an extremely sensitive galvanometer, and the pointer of the galvanometer moves over a calibrated scale to indicate the temperature. Millivoltmeters are usually built with a high internal electrical resistance, to reduce the effect on the reading of the instrument resulting from any change in the resistance of the external circuit (thermocouple, lead wires, and connections). These changes frequently occur as a result of changes in length of lead wires, deterioration, or poor connections, and if the external resistance is small compared to the meter resistance, the resulting error in readings is negligible.

In order that the current set up in thermocouple wires may be in direct proportion to the hot-junction temperature, it is necessary that the cold ends of these wires be maintained at a constant temperature, called the *cold-junction* temperature. The original method of meeting this requirement was to immerse the leads from the thermocouple in melting ice, which was extremely cumbersome. In modern instruments, this is overcome by means of a clever device (usually an expanding coil, or ordinary thermostat) which automatically changes the position of the instrument pointer on the temperature scale to correct for any changes in the temperature of the cold ends of the thermocouple wires. This device is called the cold-junction compensa-

tor, and is usually self-contained within the instrument. This means that the cold end of the thermocouple is in the instrument and that the wires from the furnace to the instrument must be of the same material as the portion of thermocouple actually in the furnace. The entire wiring from furnace to instrument is therefore actually a thermocouple, but the portion from the end of the couple proper to the instrument is called the *compensating lead wires*. In the case of platinum couples, lead wires are made of a base-metal alloy, which develops the same millivoltage as platinum, to save expense.

Although the principles upon which electrical pyrometers are based are simple, the problems of actual application are difficult. In order that any pyrometer may be practical and dependable, the galvanometer must be rugged as well as sensitive, and very good bearings and highly refined moving parts must be used throughout the construction. Adjustments for checking and counteracting all possible errors must be provided, and the mechanism must be protected from dirt, shocks, vibration, and other sources of trouble.

Simple indicating pyrometers are made both in permanent form for mounting and in portable form for test purposes. Recording pyrometers are used more than indicating types, because the permanent chart records obtained constitute one of the chief advantages to be had from the use of pyrometers. The recording feature requires elaborate and accurate mechanism in the form of a chart driven by a mechanical or electrical clock, and an inking device in connection with the pointer. These features have been very satisfactorily worked out in many commercial instruments. Figure 88 shows a view of the mechanism of a recording instrument of the potentiometer type. For automatic control, as used with all electrical furnaces and with a growing number of fuel-fired furnaces, a final addition must be made to the instrument in the form of electrical contacts provided with suitable adjustments to allow them to be set at any desired distance apart and at any point in the range of the temperature scale. Figure 89 shows a millivoltmeter type of controlling instrument.

Low-temperature Types.—In the expansion type of instrument a gas is usually the expanding medium, and such instruments are used only for low temperatures, below about 1000 deg. Fahr. The gas is contained in a bulb which is exposed directly to the heat and is connected by a tube to the instrument. The

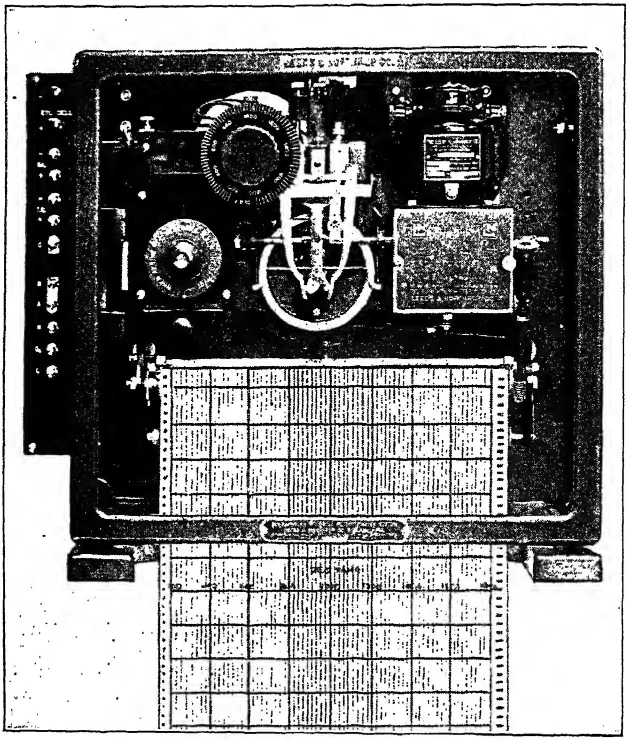


FIG. 88.—Recording Pyrometer—Potentiometer Type.

usual principle of the meter is that an increase in pressure from expansion tends to straighten a coiled tube, the moving end of which is geared directly to a pointer moving over a calibrated scale. In the resistance type of pyrometer for measurement of temperatures up to 1000 deg., the variation of the electrical resistance of a nickel or platinum helix, exposed to the heat in suitable tube or bulb, is measured by the change in

flowing through it, and the variation is read directly in degrees of temperature on a suitable calibrated scale. This method of measuring temperature is simple and extremely accurate, but is limited to low temperatures by the fact that physical and chemical changes take place in the pure metal helix at higher

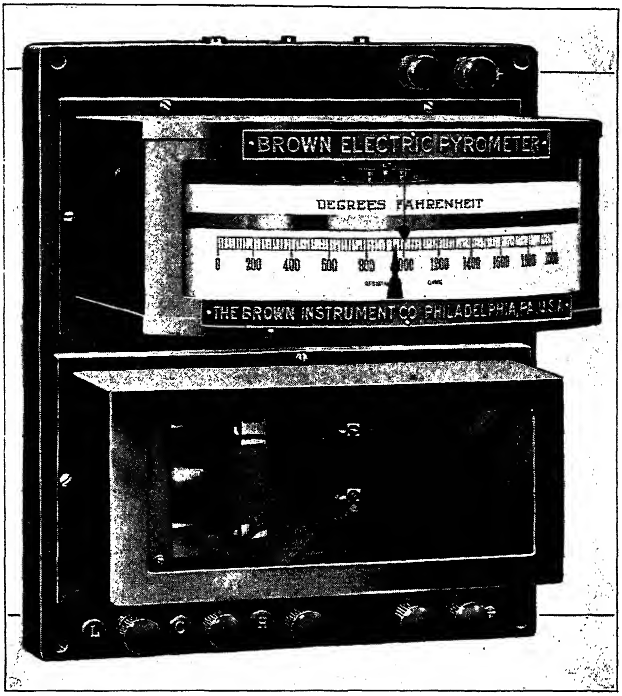


FIG. 89.—Controlling Pyrometer—Millivoltmeter Type.

temperatures and destroy the constant relation between temperature and resistance of the helix.

Radiation Type.—One form of this type of pyrometer is shown in Fig. 90. The operation is based on the principle of heat radiation, and in practice the instrument is sighted at a hole in the furnace wall. The heat rays from this sight hole fall on an objective lens in the instrument and are focused on

a minute thermocouple mounted in a small glass vacuum bulb. A very small electromotive force, which is proportional to furnace temperature regardless of the position of the lens, is developed by the thermocouple, and this force is measured by a sensitive galvanometer carried in another case. The readings are calibrated to be directly in degrees of temperature and the entire operation is simple. The advantage of the instrument is the fact that no parts are exposed to heat. Also, the rapidity of operation is a good feature, but the instrument can be made only in the indicating form, which limits its application. Its

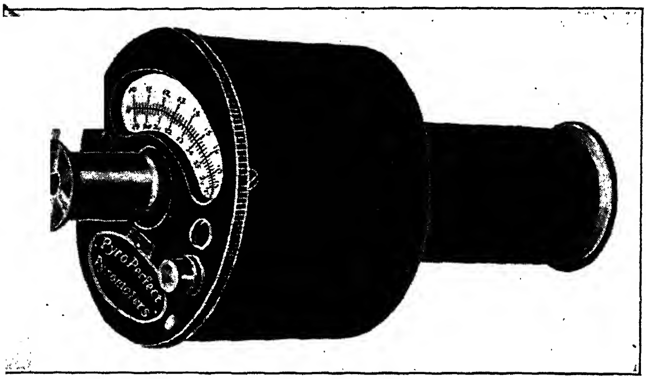


FIG. 90.—Radiation Pyrometer.

principal use is for testing purposes and for the rapid determination of the temperature of heated bodies in a furnace where this temperature is not the same as that of the furnace itself. In some cases, where the atmosphere of the furnace is not such as to approximate black-body radiation conditions, upon which the operation of the instrument depends, the makers recommend the use of a closed refractory tube inserted into a hole in the furnace wall. The instrument is then sighted into this tube, and sources of error, such as an extremely smoky condition in the furnace, are avoided. There are other forms of radiation pyrometers but the principles and operation are much the same.

Optical Types.—These instruments are similar in appearance to radiation pyrometers, but in principle they are entirely dif-

ferent, since in this case the brightness of the heated furnace or body is used as a measure of its temperature. In one form, the light rays are focused by a lens upon a prism, which in turn focuses them upon one-half of the visible field seen through the instrument. The rays from a standard lamp, lighted by a constant and standard battery, are focused upon the other side of the field. By changing a resistance in the lamp circuit the two halves of the field may be made to agree exactly in brightness, and the measure of change in the resistance is a measure of the temperature of the body. In other instruments, the filament of the lamp is projected upon the full visible field of light from the heated body, and the two made to agree. The advantage of the optical as compared to the radiation type of pyrometer is that black-body conditions are not essential and the temperatures of bodies outside of a furnace interior may be determined (scale must be removed for true readings), whereas the radiation type is good only for furnace interiors. The disadvantage is that the personal element is introduced into the determination since the comparison of brightness is a matter of personal judgment. Like the radiation type, the optical pyrometer can be made only in indicating form.

This brings us to the consideration of the automatic control of temperature.

Automatic Temperature Control

The purpose of automatic temperature control is to hold the temperature of a furnace within a few degrees of the temperature required at all times. It is evident that this condition is highly desirable in all heating operations, and in an increasingly great number of these operations it is becoming essential to good results. If it is accomplished, it guarantees a uniformity of heated product and helps to eliminate the heating equipment from suspicion in the event of failure of finished product, thus simplifying the problem of locating the source of trouble. In most manufacturing processes, the heating of the material has

been the greatest single source of trouble, and good control of temperature is a big step toward elimination of rejections and waste of material. With good automatic control of temperature, the amount of perfect product can be increased with less work, because the time and attention required to correct variations from the desired temperature are eliminated. Finally, the fuel consumption of the furnace is reduced, because the fuel used in heating the furnace to unnecessarily high temperatures, and in restoring it to normal when it drops below the desired temperature, is saved. Since there is practically no upkeep or operating expense involved, the first cost is the only disadvantage to be considered, and the problem of deciding for or against automatic control apparatus is quite simple. Each individual case calls for separate solution, based on the possibility for saving.

In cases where automatic control has been found to be justified, its successful application is accomplished only by studying the particular requirements of the furnace to which it is to be applied. The simplest case is the furnace that is maintained continuously at the same temperature and in which the heated material is all charged into the furnace at one time. In this case, the usual procedure is to adjust the different burners on the furnace to maintain uniform temperature throughout the furnace and control the main supply of fuel to the furnace automatically. In continuous furnaces with constant discharge temperature, the same procedure applies, with the controlling pyrometer at the discharge end of the furnace. In other furnaces, two or more zones for heating, soaking, etc., are required, and cannot be controlled simultaneously because the heat required by a heating zone depends upon the rate of material passing through it, while a soaking zone, which adds no heat to the material, is independent of the rate. In still other furnaces, a cycle of varying temperatures is desired and a time element must be incorporated into the control apparatus.

The simplicity of control of temperatures depends upon the fuel used. The forms of fuel, listed in the order of simplicity, are electricity, gas, liquid fuels, and solid fuels.

Electricity.—Electricity is the easiest form of heat energy to control, since its control is only a matter of closing contacts. Since the voltage of the resistor circuits of a furnace is too great for the delicate contacts of the controlling instrument, the resistor circuits are controlled through suitable relays. The control is always arranged to cut off all current to the furnace when the temperature rises above the upper limit setting of the controlling pyrometer, and to throw on full current when the temperature drops to the lower limit setting. In some cases the furnace is arranged so that the amount of full-on current can be changed by transformer taps or by electrical grouping of resistors. An example is an electric furnace for annealing castings in which the maximum input is 150 KW. connected load, obtained by a delta-circuit grouping of resistors. This input is used in heating up, and when the soaking (holding) period, which requires less heat, is reached, the resistors are changed to Y connection by a manual switch. This makes the maximum input one-third of that with delta arrangement, or 50 KW. The control still functions by supplying zero or maximum input as called for by the controller.

Gaseous Fuels.—In the case of gas fuel, the control may be required to regulate both gas and combustion air or, when modern gas burners are used, either gas or air only, because in modern burners the flow of one regulates the flow of the other (as will be seen later under the atmosphere control). The principle used in either case, and in fact in practically all automatic fuel controllers, is the same, and is to supply alternately a minimum and a maximum flow to the furnace. The minimum quantity (fuel and air adjusted for good combustion) is sufficient to maintain the furnace at a temperature below that desired, and it is supplied when the controlling pyrometer closes a contact upon reaching an upper temperature limit setting. Since the fuel is not sufficient to hold the temperature desired in the furnace, the temperature falls until the lower-temperature limit contact is made by the controller, when the maximum fuel is supplied. This supply is more than sufficient to maintain the temperature desired, and the temperature begins to gain. Mechanical repe-

tition of this action is obtained by one of four principal methods, as follows:

1. Motor-operated valves, pyrometer controlled.
   a. By-pass system.
   b. Two separate supply rates with switchover.
   c. Two settings of same valves.
2. Solenoid valves, pyrometer controlled.
3. Magnetic valves, pyrometer controlled.
4. Thermostatic valves without pyrometer.

In the motor-operated by-pass system, the gas and the combustion air pipes are both divided into two lines for a short distance. In each case, one line is the control valve line and the other is the by-pass valve line. In operation, the low fuel supply is obtained with the control valves closed and all fuel and air passing through their respective by-pass valves, properly proportioned at the beginning for good combustion. As stated above, the amount of this supply is such as to maintain the temperature at a point below that desired. The maximum fuel supply is obtained by simply opening the control valves, thus adding an additional proportioned amount of fuel and air to the main pipes to give the proper total maximum supply. The pyrometer, through high and low contacts, closes and opens these control valves full shut or full open, to lower or raise the temperature as required. The control of the motor is either through a relay or directly from the controller, depending upon the make of the valve used. Figure 91 shows one form of valve for opening and closing a single gas or air line. A double controller for simultaneously controlling both gas and air control lines uses one motor and is similar to that shown in Fig. 96 for the control of air and oil.

In the preceding type of control system the two rates of supply are obtained by using one side of the by-passes and both sides, respectively, while in the switchover type the two sides are separate and never used together. One is adjusted for the correct high rate of supply, and the other supplies the fuel at the proper low rate. The motor valve switches the supply from one

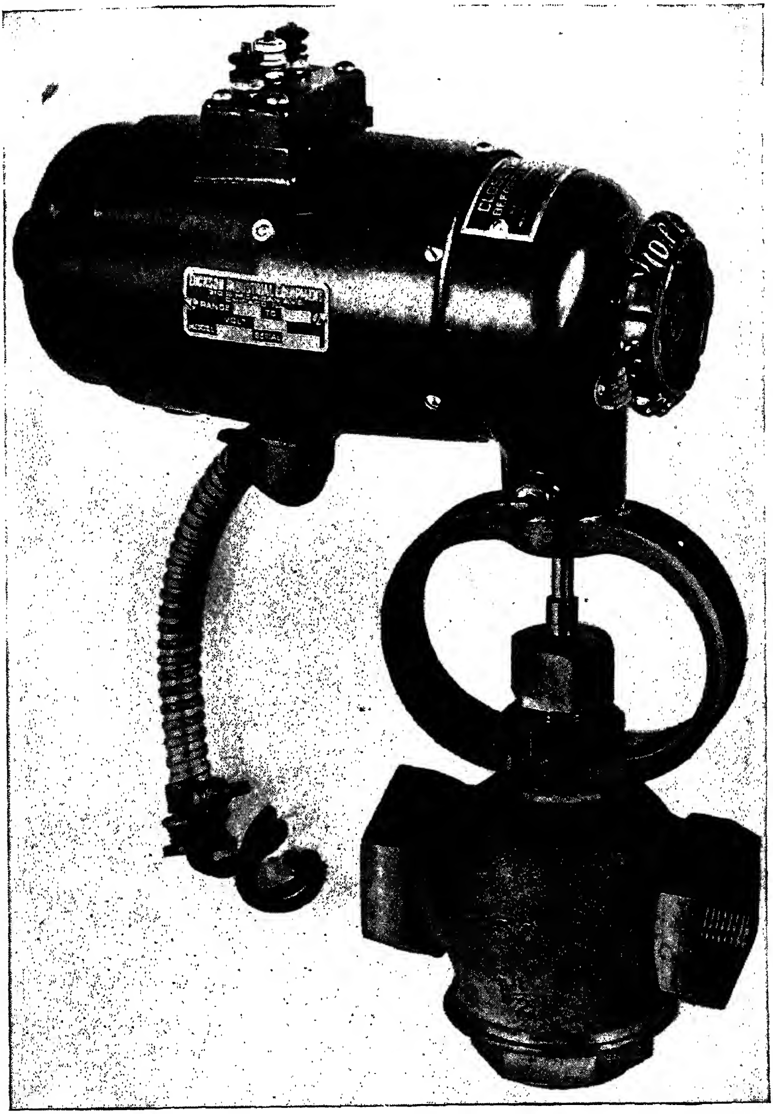


FIG. 91.—Motor Operated Valve for By-pass Control—B

side to the other. One type of this arrangement is shown in Fig. 92, where the by-pass is compactly contained within the instrument. The motor, operating through a gear reduction, switches the flow of fuel and air from one side to the other by a cam and poppet valve arrangement, and the hand valves for initially adjusting the two rates of both gas and air are clearly shown in the illustration.

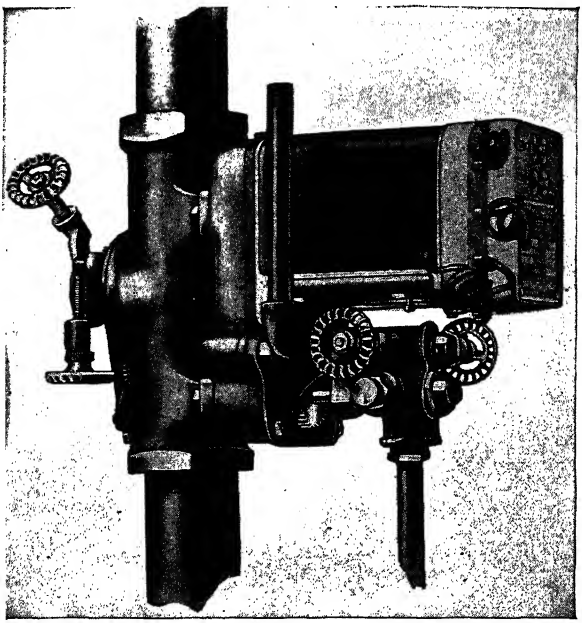


FIG. 92.—Switch-over Type of Self-contained Two-line Controller.

Another system of motor-operated valve eliminates the by-pass and obtains the two rates of flow by simultaneously changing the settings of the same gas and air valves. Figure 93 shows such an arrangement. The motor, revolving always in the same direction and operating through a gear reduction to make gradual changes and avoid sudden rushes of fuel, is controlled by limit switches to stop at the end of a stroke of the eccentric arm in either direction. The eccentric arm actuates cross-bars which change the settings of both gas and air valves at the

same time. The amount of the change and the relative change of gas and air can be adjusted so that two rates of properly proportioned fuel and air are obtained. An additional refinement is sometimes incorporated which includes a time-element feature for regulating the time that the control remains off or on to correspond to the amount of variation from normal temperature. This feature is useful only when the fluctuations of temperature are particularly rapid and violent.

Solenoid valves have a wide application to many forms of automatic control and safety valves, but are not so widely used

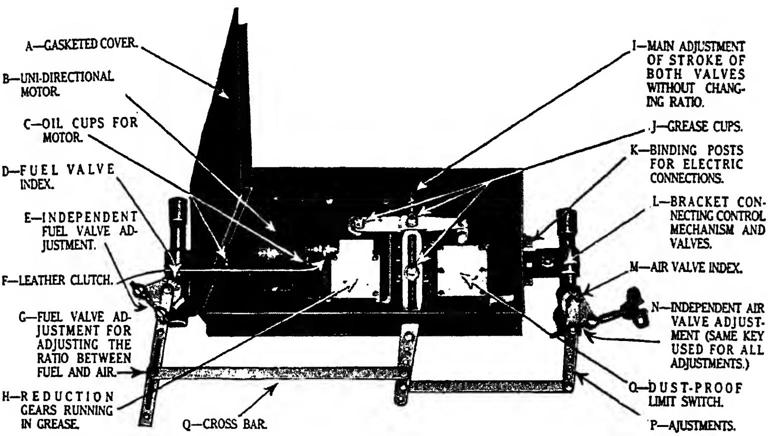


FIG. 93.—Controller Operated by Variation of Valves—No By-passes Required.

on furnace-temperature control as are motor-driven valves, the reason probably being that the abruptness of their snap action tends to cause rushes of fuel and air to the furnace, producing poor combustion and explosion hazard. This quickness of action is ideal for safety applications, and solenoid valves are sometimes used in conjunction with automatic control equipment to shut off the fuel supply in case of failure of electric current to the control equipment. In construction, a solenoid valve is simply a solenoid (electrified coil with moving core) connected to a valve. The valve is normally held shut by a spring. When electric current is supplied to the solenoid it holds the valve open

against the force of the spring and keeps it open as long as current is flowing through the solenoid.

The magnetic type of valve is similar in operation to the solenoid type, since the valve is opened magnetically and closed by springs. The construction difference is that an electromagnet with fixed core is used in place of the solenoid with moving core. Figure 94 shows one of these valves for control of oil and air. A gas valve is substituted for the oil valve when gas is the fuel. In operation, the principle is similar to the by-pass motor valve previously described, except that the by-pass is self-contained in the instrument. Minimum flow is obtained through the by-pass valves only, and maximum flow through both by-pass and magnetic valves, and change from one to the other is accomplished by fully opening and closing the magnetic valves. These valves are built up to $2\frac{1}{2}$-in. pipe size. Above that size, the air or gas pressure is utilized as the moving force to insure more positive action, this pressure is controlled by electrical means. The principle of operation is the same as with the smaller valves controlled directly by the electromagnets.

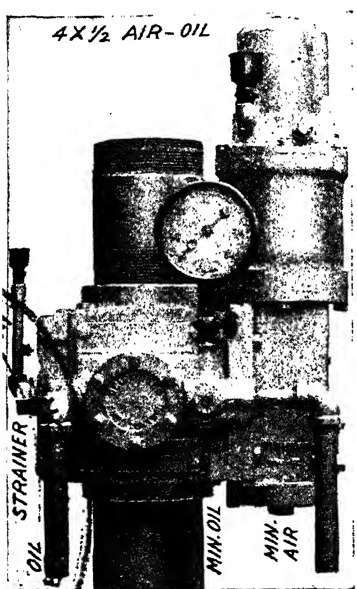


FIG. 94.—Magnetic Switch-over Type of Self-contained Two-line Controller.

Thermostatic valves operate without a thermo-electric pyrometer, but do not indicate the temperature they are controlling, so that a pyrometer is usually also employed. The action of the thermostatic valve depends directly upon the expansion of a metal rod, held by a non-expanding tube of special material. Figure 95 illustrates one of these valves, in which the gas and air valves are opened together by the single diaphragm

located above them. The operating force used is either the gas or the air exerting its pressure on the diaphragm. When the desired temperature of the expanding element (inserted in the furnace) is reached, expansion, acting through compound levers in the integral thermostatic valve, closes this valve and cuts off the pressure to the diaphragm, allowing the gas and air valves to snap shut. As the temperature drops, the expansion rod contracts and opens the thermostatic valve, which allows the controlling medium to enter the diaphragm chamber and force open the two supply valves. Both the gas and the air valves are by-passed so that when they are closed the furnace is operating on a minimum fuel feed through the by-passes. When they are open the by-pass feeds plus the valve feeds make up the proper maximum fuel feed to the furnace.

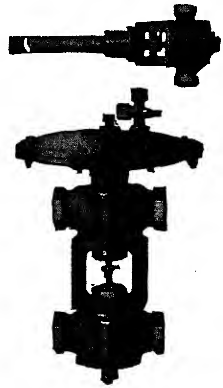


FIG. 95.—Metal Thermostatic Valve.

Liquid Fuels.—The principal liquid fuels are oil and tar, and the only difference between controllers for these fuels and for gases are those caused by the different form of the fuel. The principles of operation are just the same, and the four arrangements outlined above for gases are all used for oil. The first difference between gas and oil is that the pipes are much smaller for oil and the flow must be controlled by needle valves or other accurate forms. Butterfly valves and similar forms cannot be used for liquids. A good idea of the difference can be had by contrasting Fig. 96, showing a control for oil and air, with Fig. 91, showing the equivalent control for gas or air only. On account of the density of liquid fuels, controlling valves should not be set above the level of the burners, because the pipes will drain and continue to supply oil to the burners after the valve is closed. It is also advisable, in controls for liquid fuels, to time the opening of oil and air valves, rather than to have them open and close simultaneously as is satisfactory for air-gas control. In liquid controls, the air should come on slightly

ahead of the oil in opening, to be sure that the oil will have sufficient air to carry it into the combustion chamber. In closing, the oil should turn off slightly ahead of the air so that all the oil will be carried out of the pipes and not left in excess to smoke and carbonize.

Figure 97 shows a motor-driven control of the by-pass system, as described for gaseous fuels, for oil and air. The by-passes are

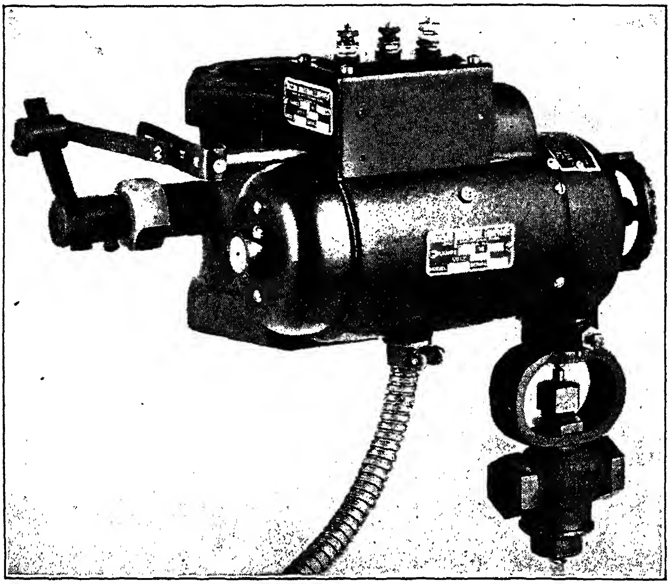


FIG. 96.—Motor-operated Oil and Air Valves for By-pass Control—By-passes not Shown.

not shown, and the oil and air valves shown simply open and close by the action of a motor operating through a gear reduction and system of levers. A magnetic or mechanical brake is provided to prevent drift of the motor after the limit switches have cut off the supply of current. The action of the levers is clearly shown in the illustration.

Solid Fuels.—The automatic control of temperature by control of solid fuels has received little or no attention in ir trial furnace applications. Powdered coal and stoker-

can both be controlled, and the advances that have been made in power plant practice with these fuels will eventually be applied to industrial furnaces. The principles and practice of powdered-coal control should be similar to those for oil, since the characteristics of these two fuels are similar. For stoker-fired coal, the control necessitates the interconnection of regulation of

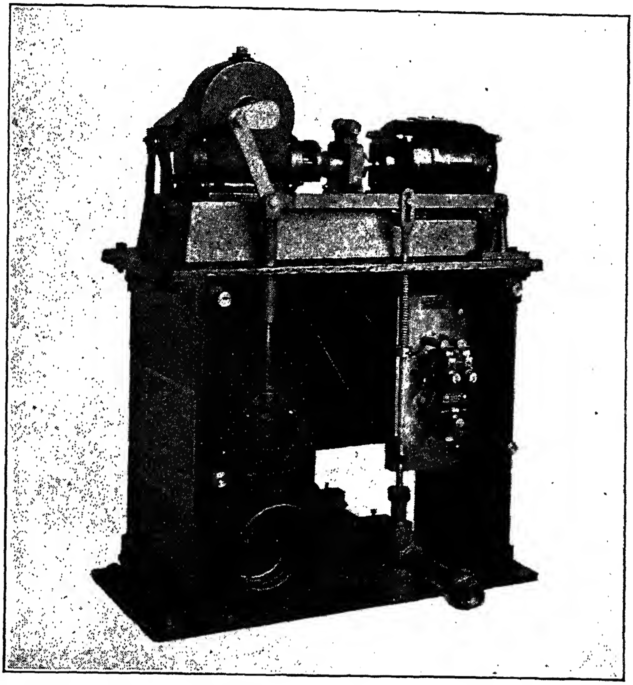


FIG. 97.—Motor-operated Oil and Air Valves for By-pass Control—By-passes not Shown.

stoker speed and damper or fan supply of combustion air, depending upon whether the air is supplied by stack or by forced draft.

AUTOMATIC CONTROL OF FURNACE ATMOSPHERE

As seen from the above outline, automatic temperature control is also accompanied by a degree of atmospheric control. feature is essential since the necessity for hand adjustment

of fuel-air ratio to follow changes in fuel feed would eliminate the advantage of automatic temperature control. This necessity is the reason for the adjusted maximum and minimum fuel feed principle used in the above temperature controls, rather than the exclusive use of an evidently ideal throttling method whereby the fuel feed would gradually change to suit temperature variation.

True automatic atmosphere control consists of an arrangement whereby the regulation of either fuel or air automatically causes a change in the other to keep the two always in the proper ratio for combustion. Fundamentally, each pound of combustible in the fuel requires a definite constant weight of oxygen for combustion, but it is a long step between this simple fundamental rule and the actual practical attainment of a constant ratio. The variables to be automatically taken care of are many, and include variation in combustible content of fuel, force supplying fuel and air to the furnace, and densities of fuel and air. Due to the great difference between the characteristics of flow of liquids and air and of solids and air, no satisfactory device has been developed for accurately proportioning the combustible of these fuels with the oxygen of the air for all conditions. The various methods of accomplishing this result for gases are well described in detail in *Industrial Furnaces*, Vol. II, by Professor W. Trinks, and will not be repeated here except to give an outline of the methods, which are as follows:

Interconnected gas and air valves.
Unit blower systems with mixing valves.
Aspirating Venturi tube mixers, air inducing gas.
Aspirating Venturi tube mixers, gas inducing air.
Balanced pressure drop proportionators.

The logical method of regulating furnace atmosphere would be continuously to analyze the atmosphere of the furnace for excess air and unburned fuel, and to regulate the fuel and air supply to correct variations from the desired conditions, but to date no practical apparatus has been developed to carry out this procedure.

Automatic Pressure Control

Very little attention has been paid to this form of furnace control, although the advantages of such regulation are evident, if only in fuel saving by preventing infiltration of air from excessive draft. Since pressure depends upon the amount of fuel burned and the means for escape of the combustion gases, any method of control must operate through a pressure-measuring device to change the resistance to escape of furnace gases to correspond to changes in amount of fuel burned. Application has been limited to remote instances of large continuous furnaces utilizing stack draft, where a pressure-measuring instrument, set at about 0.01 in. of water pressure, has operated a mechanism for opening and closing a damper at the top of the stack to correct pressure variations from this setting. The results have been very satisfactory in every respect, and further application is warranted.

Financial Consideration of Automatic Control

In the beginning of this chapter we saw the principal advantages of automatic control. Now that some of the different methods of control have been described, it is not out of place to repeat these advantages as a guide in the consideration of control equipment. The first step in such a consideration is to study each of the advantages in detail with respect to the particular installation under consideration, as follows:

1. *Fuel Saving.*—This may vary from zero to 40 per cent, depending upon the amount of heat being lost without automatic control from excessive variations from desired temperature.
2. *Labor Saving.*—Depends upon how much other useful work can be accomplished by the furnace tender if he is relieved of the necessity for constant supervision of the furnace. In many cases a man can be eliminated.
3. *Increase in Production.*—Depends upon the amount of time being lost without automatic control in restoring

the temperature of the furnace to normal when it varies through poor control of fuel.

4. *More Satisfactory Product.*—Depends upon the requirement of the process in temperature uniformity and furnace atmosphere. This includes physical properties of the product as the result of heat treatment and surface characteristics as the result of oxidation.
5. *Elimination of Waste.*—Depends upon the amount of rejection of product without automatic control that could be eliminated with control.

The final answer is to compare the total of these advantages, converted into terms of dollars and cents as closely as possible, with a quotation on the cost of the necessary control equipment. In many cases this comparison will show a handsome return on the investment, but in others there will be found no justification for the installation of automatic control.

In conclusion, it should be said that there are other makes of control equipment of equal value with those mentioned in this chapter, but the principles are in most cases the same as for those mentioned. The purpose is to cover the chief principles of operation upon which automatic control is based and to clarify the most confusing factors which complicate a consideration of furnace control. This outline of furnace control is a fitting conclusion to this book on practical furnace design, because it is logical that a furnace, designed and constructed on carefully considered theory, should be protected as far as is practically possible from the injurious effects of careless and ignorant operation.

CHAPTER

PRACTICAL PROBLEMS IN FURNACE

THE purpose of this chapter is to illustrate, by several examples, the application of some of the principles which have been considered in the preceding chapters to a few of the many and varied questions which arise in the selection and design of furnace equipment. The available technical data and the development of theory of furnace design are still inadequate for any exact solution of the many problems, and there are few formulas that may be applied automatically to produce answers of any value. The result of this condition is a general lack of confidence in theory as applied to furnace design and a tendency to avoid its use wherever possible.

It is true that experience with no knowledge of theory is of more value in producing satisfactory results than all of the known theory when not accompanied by actual experience in the design and operation of furnace equipment, but it would seem that the combination of experience and theory should be stronger than either by itself. In the following examples, all of which are based on actual problems, the attempt is made to show that theory may be of great assistance in answering practical questions.

The theory used in the problems, and that which has been given throughout the book, is as simple and as practical in nature as is consistent with necessary accuracy. In some cases, exactness is sacrificed for simplicity, and this appears to be a logical practice until more exact data are available. When that time comes—and it will come soon, because increasing attention is being devoted to the subject of heat—exact theory will also appear simple; until it comes, available theory in simple form should be taken advantage of in design.

Example I: Utilization of Gas at Low Pressure

In this example, a furnace is fired by artificial gas at low pressure and the problem is to check the size of the piping. The conditions are as follows:

1. Gas is supplied in a known quantity and at a known line pressure to a meter located in the basement of a shop. The details of the piping from the furnace to this meter are known, as is the maximum quantity of gas required by the furnace.
2. Air is supplied by a blower which is located near the furnace, and whose characteristics are known.

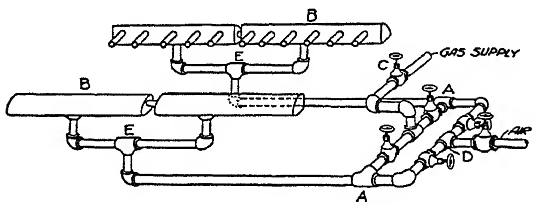


Fig. 98.—Arrangement of Gas-fired Furnace Piping.

3. The furnace piping is generally as shown in Fig. 98. The gas and air are supplied to two ordinary tees A, and the mixture is conveyed from these tees to two manifolds B, which contain a number of burner orifices.
4. The problem is to proportion the piping sizes and burner orifices properly to burn the required quantity of gas in the furnace.

Assume that tests have shown that at the meter in the basement a maximum of 1560 cu. ft. of gas per hour is available, and that the pressure at full flow is 4.0 in. of water. Air is supplied by a small constant-volume blower, rated at 7000 cu. ft. of free air per hour at a delivery pressure of 12.5 in. of water. As shown in Fig. 98, the gas and air mixture enters the furnace through the orifices in the burner manifolds on each side of the furnace. The problem is to determine what size of piping is required to deliver 1400 cu. ft. of gas per hour (known to be required by the furnace) at sufficient pressure to prevent back-firing at the orifices. The following reasoning must be understood for the solution of the problem:

1. The pressures of gas and air entering the mixing tees must both be greater than the pressure of the mixtures leaving these tees, and all the pressures should be as nearly the same as possible. If this is not true, the flow to or from the tees will be interrupted, and the desired quantity of gas and air will not be properly mixed. Since the air is supplied by a blower capable of delivering it at a higher pressure than the available gas

pressure, the most common source of trouble in such an arrangement is the partial stoppage of the flow of gas at the mixing tees, due to too high air pressure. The remedy is to reduce the air pressure until it is near that of the gas, by proper air piping and valves, and to keep the pressure of the leaving gas-air mixture below the air and gas pressures at the tees by proper piping design beyond the tees.

2. The pressure of the gas at the tees is dependent upon the available gas-line pressure at the meter, the quantity of gas required, and the resistance encountered in piping, fittings, and valves. These resistances can be calculated, as will be shown. The gas pressure is ordinarily the lower, and therefore the determining pressure at the tees.

3. The pressure of the air at the tee is dependent upon the pressure which the blower develops when delivering the required quantity of air, and upon the pressure drop through the piping and control valves.

4. The pressure of the mixture leaving the tees is dependent upon the quantity of gas and air mixed, the pressure drop through the mixture piping, the size of the final nozzles, and the velocity required at the nozzles to prevent back-firing into the nozzles.

The following method is followed in making the actual calculations required:

Determination of Available Air and Gas Pressure at Mixers.—The gas piping between the meter in the basement and the mixing tees A consists of 127 ft. of 2-in. pipe, ten 2-in. elbows (equivalent to 5 ft. of straight pipe each), and one gate valve, as shown at C (equivalent to 5 ft. of 2-in. pipe). The total equivalent straight pipe is then 182 ft. If the specific gravity of the gas is 0.5, the pressure drop with a flow of 1400 cu. ft. per hour (23.3 cu. ft. per min.) through 182 ft. of 2-in. pipe (2.07 in. inside diameter) is:

$$\frac{Q^2sL}{1323D^5} = \frac{(23.3)^2 \times 0.5 \times 182}{1323 \times (2.07)^5} = 1.0 \text{ in. of water (from Chapter VII).}$$

The maximum pressure at the mixing tees is then:

$$4.0 \text{ (at meter)} - 1.0 = 3.0 \text{ in. of water for maximum flow.}$$

The air piping from the blower to tee D in Fig. 98 consists of 7 ft. of 2-in. pipe, three elbows, and one gate valve, or an equivalent length of 27 ft. of 2-in. pipe. The piping from D to each mixing tee is 4 ft. of 2-in. pipe, one elbow, and one gate valve, or a total equivalent of 14 ft. of straight 2-in. pipe. Each cubic foot of the artificial gas requires 5 cu. ft. of air for proper combustion, so that the maximum air flow is 7000 cu. ft. per hour. By the above formula, for this flow of air, the pressure drop through the 27 ft. of 2-in. pipe is:

$$\frac{(117)^2 \times 1.0 \times 27}{1323 \times (2.07)^5} = 7.4 \text{ in. of water.}$$

For half this quantity of air flowing through the 14 ft. of pipe from D to each mixing tee, the drop is 1.0 in. of water. The air pressure available at the mixers for maximum flow is then:

$$12.5 \text{ (at blower)} - (7.4 + 1.0) = 4.1 \text{ in. of water.}$$

This indicates that ample pressure is available. The operating pressure is adjusted to suit the gas pressure by means of the valve. The resultant pressure of air and gas at the mixers will be about 3.0 in. of water with maximum gas flow and with 5 to 1 ratio of air and gas quantities.

Determination of Pressure Drop through Burner Orifices.—The size of these orifices is fixed by the minimum velocity at which properly proportioned gas-air mixtures can enter the furnace without back-firing. Information on these velocities is meager, but for small orifices the safe minimum velocity for gas-air mixture (properly proportioned for combustion) is about 30 ft. per sec. for artificial gas and for coke-oven gas, and 10 to 15 ft. per sec. for natural gas.

For satisfactory furnace operation, an allowable turn-down of at least 50 per cent of maximum capacity must be provided without back-firing. In the case of the example, a minimum flow of 600 cu. ft. of gas and 3000 cu. ft. of air per hour is provided, and, with a minimum velocity of 30 ft. per sec. at this flow (artificial gas-air mixture), the total area of the orifices is:

$$\frac{3600 \text{ cu. ft.} / \text{hour} \times 144 \text{ sq. in.} / \text{sq. ft.}}{3600 \text{ sec.} / \text{hour} \times 30 \text{ ft.} / \text{sec.}} = 4.8 \text{ sq. in.,}$$

for both sides of the furnace, or 2.4 sq. in. on each side. This area is made up of 87 holes, each $\frac{3}{16}$ in. in diameter, on each side of the furnace.

At maximum flow, the amount of mixture passing through each hole is:

$$\frac{1400 \text{ cu. ft. gas} + 7000 \text{ cu. ft. air}}{174 \text{ holes}} = 48.3 \text{ cu. ft.} / \text{hour,}$$

and, from Table 25 in Chapter VII, the pressure drop through the orifices is 0.9 in. of water.

Determination of Pressure Drop from Mixing Tees to Orifices.—Since the delivery pressure from the spuds into the furnace is practically atmospheric, the back-pressure at the delivery side of the mixing tees is equal to the sum of the drop through the orifices, just determined, and the pressure drop in the piping from the mixing tees to the orifices. We saw in the beginning that the back-pressure must not be as great as the pressure on the delivery side of the mixing tees (3.0 in. of water from above) if the required flow is to be maintained.

Half of the total gas-air mixture, or 70 cu. ft. per min., passes through the piping from each mixer to points E. This piping consists of 5 ft. of

$2\frac{1}{2}$-in. pipe and one elbow: and the pressure drop, by previous method of calculation (specific gravity of mixture taken as 1.0), is 0.4 in. of water. At points E, the quantities again divide, each half (2100 cu. ft. of mixture per hour) passing through 3 ft. of $1\frac{1}{2}$-in. pipe with two elbows, and the pressure drop is 1.1 in. of water. The back-pressure in the mixers is then:

$$0.9 + 0.4 + 1.1 = 2.4 \text{ in. of water,}$$

which is less than the 3.0 in. of water which has been found for the delivery pressure in the mixers. The piping and orifice sizes as outlined are therefore correct. This example was taken from an actual installation, which did not operate satisfactorily until the piping was increased to the sizes used above, as the result of just such a theoretical calculation, and the measurement of pressures agreed closely with the values which have been determined in the above calculations.

With a thorough understanding of the methods used in this example, it should be possible to make similar analyses of other gas-burning arrangements. As in the case of the example, the burners usually fire into a furnace in which a very slight pressure exists, and the only air in the furnace is that which is supplied through the mixing tees by the blower. However, in many cases, as in that of atmospheric burners in large ovens or other low-temperature equipment, a different condition exists. When a mixture of gas and an incomplete supply of air emerges from an orifice in such a case and burns in the air, it picks up, or entrains, a certain amount of secondary air for combustion from the surrounding air. The amount of air entrained varies with the pressure and density of the issuing gases and with the diameter and form of the jet. Information on the subject is rather scarce, but the author has found that, with natural gas, an air-gas mixture issuing from a $\frac{1}{4}$-in. diameter hole at the rate of about 14 ft. per second will entrain about 50 per cent of the air needed for good combustion, the other 50 per cent being in the mixture leaving the holes. For the same velocity through a $\frac{3}{4}$-in. diameter hole, the percentage entrained drops to about 30 per cent, and with a $1\frac{1}{2}$-in. diameter hole, less than 10 per cent was found to have been picked up by the jet. From these figures it is evident that when gas burns in the open from so-called atmospheric burners, the manifold orifices and piping must be

designed to take care of only part of the combustion air required. This is also true of the many forms of inspirating burners, where part of the air is induced into the furnace through the gas burner by the high-velocity jet from the burner.

Example II: Use of Stacks with Furnaces

This example is intended to illustrate the use of theory to establish an opinion which is based on experience. The question involved the recommendation of a rolling-mill furnace to be built without a stack to replace an old furnace which was equipped with a stack. The furnace was a simple

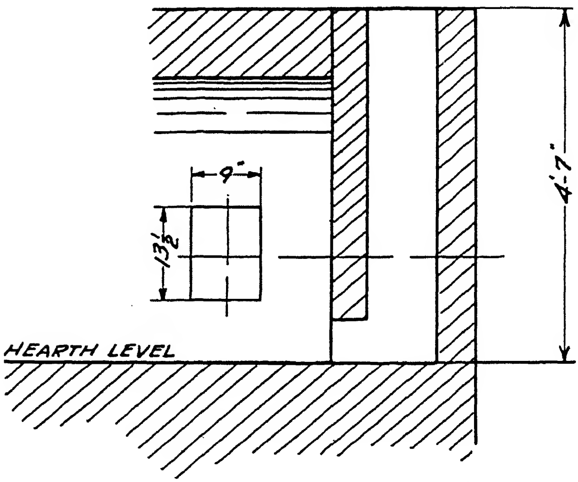


Fig 99.—Arrangement of Flue in Furnace Sidewall.

batch-type, with doors along the front and burners at the ends. Confidence in the recommendation was gained from the following analysis:

In order to study comparative conditions with and without stacks, a furnace was selected having a hearth area of 70 sq. ft., a normal production of 2.45 tons of steel heated per hour to 2200 deg. Fahr., and an oil consumption of 73.5 gal. of oil per hour, which amounts to 30 gal. of oil per ton of steel. In operation, the loaded furnace is brought up to temperature and held until it has been emptied by the demands of the mill. The method of comparison will be to determine the size and number of flues of the type illustrated in Fig. 99 and the dimensions of flues and stack as shown in Fig. 100, which are necessary to take care of the above operating conditions. Then, in each case, the variation in furnace pressure will be determined for variations in oil consumption from the normal.

Arrangement with Outside Flues.—For high-temperature furnaces of this kind, the flues may be either in the roof or in the sidewalls, the slight advantage of either arrangement depending largely upon the nature of the material to be heated. In this case the flues are located in the sidewalls as shown in Fig. 99. With an average temperature of 2050 deg. Fahr. in the flues and an allowable velocity of 22 ft. per sec. for the flue gases, eight flues, each 9 in. × $13\frac{1}{2}$ in. were selected. With this arrangement and the dimensions shown, the draft available from these flues [1] is:

$$0.01468H\left\{1 - \frac{522}{T + 460} \times \frac{q_g}{q_a}\right\}$$

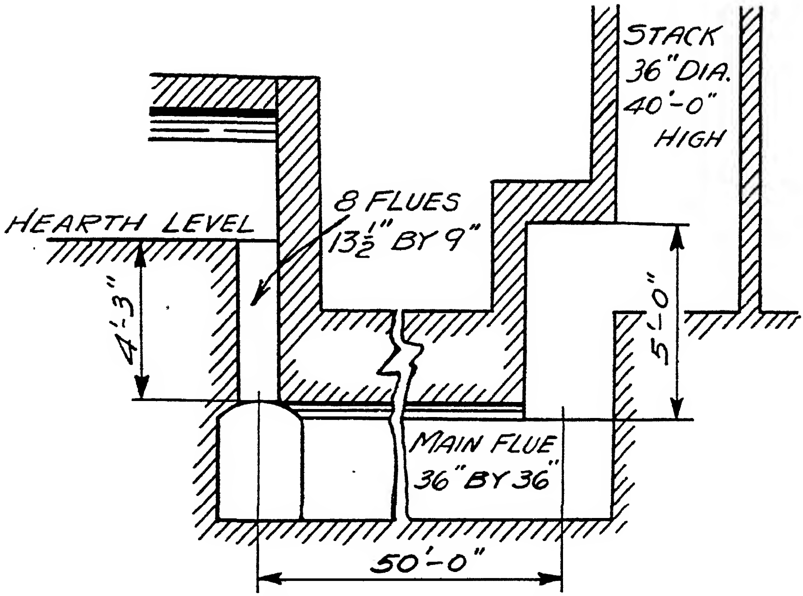


FIG. 100.—Arrangement of Underground Flue from Furnace to Stack.

where H is the height in feet, T is the average temperature in degrees Fahrenheit, and $\frac{q_g}{q_a}$ is the ratio of density of the flue gases to density of air at the same temperature and pressure (taken as 1.0 in most cases). The draft is then:

$$0.01468 \times 4.5\left(1 - \frac{522}{2510}\right) = 0.0531 \text{ in. of water.}$$

[1] For formulas and complete explanation of methods of calculation of drafts and pressure drops, see *Industrial Furnaces*, Vol. I, Chapter VI, by W. Trinks.

For normal operation with an average fuel oil (140,000 B.t.u. per gal.) consumption of 73.5 gal. per hour, the quantity of flue gases produced is 149 cu. ft. per sec. at 2050 deg. Fahr. (by methods of Chapter V in this book). The velocity in each flue is 22 ft. per sec., and the coefficient of friction is $\frac{1.29}{10,000}$ (Fig. 225 in Trinks' *Industrial Furnaces*, where

$$\frac{cD}{\mu} \quad \frac{4c \times A}{12\mu \times B}$$

for a rectangular duct). The loss due to friction, from the formula:

$$\frac{119.1 \times f \times B \times L \times c^2}{A(T + 460)} \times \frac{q_g}{q_a}$$

in *Industrial Furnaces*, is then 0.005 in. of water. The loss due to velocity head, from the formula:

$$\frac{0.184c^2}{T - 460} \times \frac{q_g}{q_a},$$

is 0.0354 in. of water, and the loss from one right-angle bend, from the formula:

$$\frac{0.118c^2}{T - 460} \times \frac{q_g}{q_a},$$

is 0.228 in. of water. The pressure in the furnace for normal operation is, therefore:

$$0.005 + 0.0354 + 0.0228 - 0.0531 = 0.01 \text{ in. of water},$$

which is the desirable pressure for good furnace operation.

Arrangement with Flues and Stack.—As shown in Fig. 100, the flues selected for a furnace of this size with a stack consist of eight downtakes, each 9 in. × 13½ in., connected by a header flue to the main 36-in. × 36-in. flue, which extends underground a distance of 50 ft. to the stack. The stack is made 30 in., inside diameter, and 40 ft. high, these dimensions being about as small as practicable to insure easy lining and extension above surrounding buildings. With these dimensions of flues and stack, and normal operation of the furnace, the total losses from friction, velocity head, and bends were calculated by the preceding methods to be about 0.146 in. of water, based on estimated temperatures at different points in the flues and stack. Calculations of this nature cannot be exact, but they can be close enough for the purposes of our present comparison. The net useful draft of the stack and flues was calculated to be 0.441 in. of water, so

that in order to produce a pressure in the furnace of 0.01 in. of water at normal operation, the flue damper must be closed until it offers a resistance of 0.305 in. of water, which means that a damper placed in the main flue will be open only about 8 in. for normal operation (Fig. 222, *Industrial Furnaces*, Vol. I).

To compare the furnace pressure under different conditions, it was assumed that the damper is not changed with changes in the fuel consumption. This is entirely logical in practically all cases, because, although the rate of firing is constantly varied to maintain a desired temperature, the damper is seldom moved and is frequently so rusted that it cannot be moved. Also, the usual damper arrangement cannot control the draft to within 0.01 in. of water with manual operation. In this instance, for example, calculation shows that a variation of $\frac{1}{2}$ in. in the vertical setting of the damper will change the furnace pressure about 0.05 in. of water. In addition, it must be assumed that the variations from average fuel consumption are not of sufficient duration greatly to change the flue temperatures. Observations indicate that, owing to the balancing effect of the brickwork, these temperatures do remain practically constant in spite of wide fluctuations in fuel consumption.

Variation of Furnace Pressure.—Having determined the dimensions of flues for the same furnace with and without a stack, we can now calculate the various losses in these flues in each case for different quantities of flue gas corresponding to different rates of firing. The drafts will remain constant for all rates, as we have assumed that the flue temperatures will remain practically constant. The difference in every case will represent the resultant furnace pressure, and for each rate we can determine the percentage of variation from the normal 0.01 in. of water pressure in the furnace. These values have been calculated and are summarized in the following table and shown graphically in Fig. 101.

FURNACE WITHOUT STACK

	Percentage of Normal Fuel Consumption					
	25	50	75	100	125	150
Draft	Remains constant at 0.0531 in. of water					
Total losses	0.0040	0.0160	0.0362	0.0631	0.0986	0.1423
Furnace pressure	−0.0491	−0.0371	−0.0169	0.01	0.0455	0.0892
Percentage variation from 0.01 in.	591	472	269		455	892

FURNACE WITH STACK

	Percentage of Normal Fuel Consumption					
	25	50		100	125	150
Draft	Remains constant at 0.4408 in. of water					
Total losses	0.0285	0.1136	0.2537	0.4508	0.7037	1.0126
Furnace pressure	−0.4123	−0.3272	−0.1871	0.01	0.2629	0.5718
Percentage variation from 0.01 in.	4223	3372	1971		2629	5718

From a study of Fig. 101, it appears that (1) furnace pressure varies rapidly with variation in fuel consumption, from the nor-

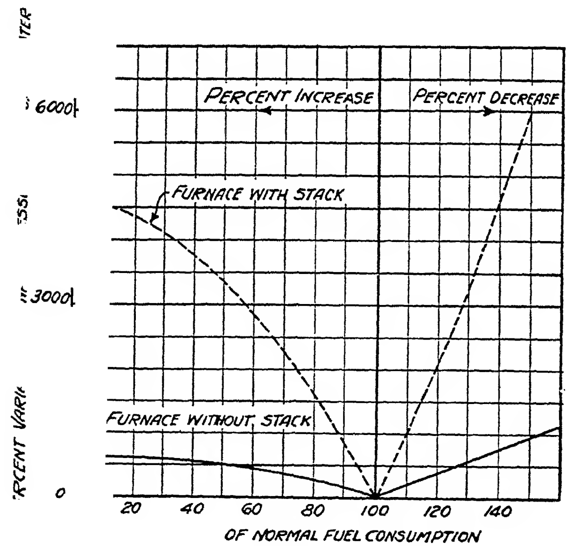


FIG. 101.—Variation of Furnace Pressures with Fuel Consumption.

mal for which the furnace is designed and adjusted, the proportionate increase being greater for increase in fuel consumption over normal than for decrease below normal; and that (2) the change in furnace pressure is much greater for a furnace equipped with a stack, with the result that much more excess air is drawn

into the furnace through every opening or forced out of the furnace each time that the fuel

From this it appears logical to conclude that in of fuel consumption, as well as of the quality of the heated material, stacks should be omitted or disconnected from furnaces wherever possible. This is true of furnaces that do not require the stack for overcoming unusual resistances to the flow of the waste gases. A stack must be used with long continuous furnaces or with furnaces equipped with recuperators or regenerators to insure the flow of the gases. Figure 101 also illustrates the possibilities for the development of some form of automatic pressure control. Unsuspected quantities of cold air are drawn into furnaces and large quantities of heat forced out of them by the magnified variations in furnace pressure resulting from changes in the fuel consumption.

Example III: Heat Losses from Furnace Openings

The general purpose of this example is to outline a more accurate method of calculating the heat radiated from furnace openings than the quick method of estimating which was included in Chapter V. The specific problem involved is to determine the additional amount of fuel oil which is required to maintain a temperature of 1600 deg. Fahr. in the furnace of Fig. 25 when the door remains open to a height of 18 in. for ten minutes.

The transfer of heat by radiation inside of a furnace can be determined in most cases by using directly the values of black-body radiation given in Fig. 54. These values can also be used in determining the heat radiated to the outside through furnace openings, but the effect of the shape of the opening, re-radiation from the sides of the opening, and other factors must be taken into consideration and will alter the values obtained by the direct use of Fig. 54 (which is reproduced here from Chapter V for convenient reference). The effect of the various factors has been studied and discussed by Mr. J. D. Keller in *Fuel and Furnaces*, issue of December, 1927 (Published by F. C. Andresen and Associates, Inc., Pittsburgh, Pa.), and the correction factors to be used for different conditions are given in that publication. Table 28, which has been prepared from these data, gives the factors by which the values of Fig. 54 must be multiplied to obtain the actual total heat, in B.t.u. per square inch, which is radiated from furnace openings of different proportions in walls of the thicknesses commonly used in furnace construction.

For the present example, the width of the door of Fig. 25 is assumed to be 36 in., the wall thickness 9 in., and the height has been stated as 18 in. From Table 28, the proper factor is, therefore, 0.70. From Fig. 54, the direct radiation for 1600 deg. Fahr. temperature is 200 B.t.u. per square inch per hour. The actual radiation is then:

$$0.70 \times 200 = 140 \text{ B.t.u. per square in.} / \text{hour.}$$

The heat radiated from the opening in ten minutes is:

$$\tfrac{1}{6} \times 36 \text{ in.} \times 18 \text{ in.} \times 140 = 15{,}100 \text{ B.t.u.}$$

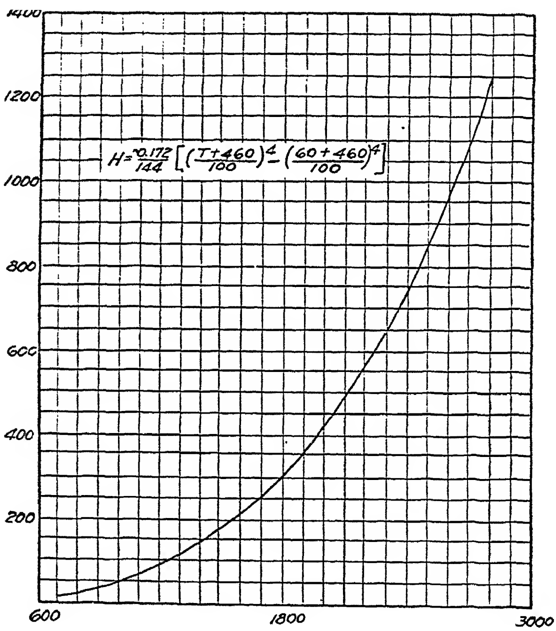


FIG. 54.—Variation of Black Body Radiation with Temperature. (Repeated from Chapter V.)

Now, in the discussion of insulation in Chapter VI we saw that the thermal efficiency of a furnace fired by fuel oil to 1600 deg. Fahr. is 63 per cent $\left(\frac{\text{heat in fuel} - \text{heat lost to flue gases}}{\text{heat in fuel}}\right)$. In other words, only 63 per cent of the heat in the fuel is available for useful work or for offsetting losses other than the loss to the products of combustion. Therefore, in this case, for oil of 140,000 B.t.u. per gal., only 0.63 × 140,000, or 88,200

B.t.u. per gallon, is available to offset the door loss. The oil required is then:

$$\frac{15,100}{88,200} = 0.17 \text{ gal.}$$

TABLE 28

MULTIPLICATION FACTORS TO BE USED IN OBTAINING ACTUAL RADIATION FROM DIRECT RADIATION VALUES OF FIG. 54

Thickness of Wall, Inches	Width of Opening, Inches	Height of Opening, Inches				
		6	12	18	24	30
$4\frac{1}{2}$	6	0.56	0.63	0.66	0.68	0.69
	12	0.63	0.70	0.73	0.76	0.78
	24	0.68	0.76	0.80	0.82	0.84
	36	0.71	0.79	0.83	0.85	0.87
	48	0.72	0.81	0.85	0.87	0.89
	60	0.73	0.82	0.86	0.89	0.91
9	6	0.43	0.49	0.52	0.55	0.56
	12	0.49	0.56	0.60	0.63	0.64
	24	0.55	0.63	0.67	0.70	0.72
	36	0.57	0.66	0.70	0.73	0.75
	48	0.59	0.68	0.72	0.76	0.78
	60	0.61	0.69	0.74	0.77	0.79
$13\frac{1}{2}$	6	0.36	0.42	0.45	0.47	0.49
	12	0.42	0.48	0.52	0.55	0.57
	24	0.47	0.55	0.59	0.62	0.64
	36	0.50	0.58	0.63	0.66	0.69
	48	0.52	0.60	0.65	0.68	0.71
	60	0.53	0.61	0.66	0.70	0.72
18	6	0.31	0.36	0.39	0.42	0.43
	12	0.36	0.43	0.46	0.49	0.51
	24	0.42	0.49	0.53	0.56	0.58
	36	0.45	0.52	0.57	0.60	0.62
	48	0.47	0.55	0.59	0.63	0.65
	60	0.48	0.56	0.61	0.64	0.67

This fuel consumption is for a period of ten minutes, so that if the door were open constantly to a height of 18 in., the fuel required to offset the resulting loss would be about one gallon of oil per hour. The method of calculation which has been outlined is not at all difficult, and its application to other instances will show that a considerable quantity of fuel is wasted over a period of time by leaving furnace doors open unnecessarily.

Example IV: Study of Furnace Height

This example is an attempt to determine, by the application of simple theory, the effect of furnace height on the ability of a furnace to take large charges of cold material with a minimum temperature drop. It is sometimes contended that furnaces into which a large piece of cold material is charged should be designed with very high heating chambers, in order to possess the stored heat necessary to prevent large temperature fluctuations. Since

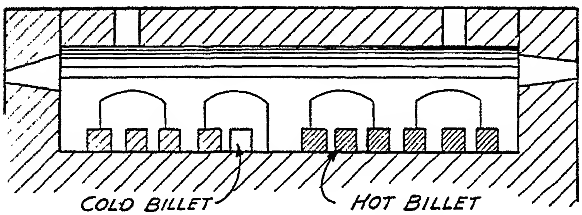


Fig. 102.—Arrangement of Direct Fired Furnace and Heating Billets.

high chambers cause poor fuel economy, it is worth while to determine, as far as possible, to what extent the height is effective in equalizing temperatures.

The following theoretical analysis is based upon a furnace which is 15 ft. long by 8 ft. wide by 2 ft. high to the arch skew, with doors located along the front. It is used for heating six billets for forging per hour, each billet being 8 in. in diameter and 72 in. long, with a weight of 1050 lb. Each door is 18 in. wide by 20 in. working height. The furnace roof is of 9 in. of firebrick, front wall of $13\frac{1}{2}$ in. of firebrick, side and back walls of 18 in. of firebrick, and hearth of $14\frac{1}{2}$ in. of firebrick. The temperature in the furnace is 2300 deg. Fahr., and the furnace is fired by fuel oil as shown in Fig. 102.

In operation, a hot billet is removed and a cold one charged every ten minutes. The fuel adjustment is not changed when the cold bars are charged, so that the heat input remains practically constant at all times during steady operation.

The problem is to determine a numerical value for the effective heat-storage capacity which is available for insuring temperature stability, and

to determine how this capacity is distributed and how much it would be increased by making the furnace 6 ft. high, or three times its present height.

If we assume that the average temperature drop of the 2-ft. high furnace does not exceed 25 deg. in the first minute after each charge (this seems reasonable from observations of furnaces of this type), the temperature and heat requirements during each cycle of ten minutes will be somewhat as shown graphically in Fig. 103. In that illustration, the upper diagram

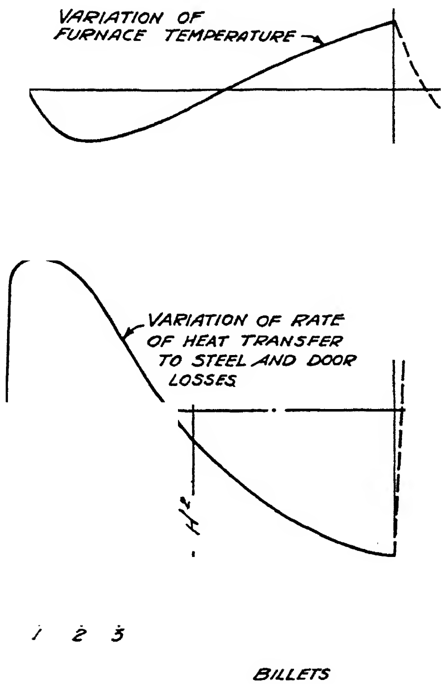


FIG. 103.—Variation of Temperature and Heat Absorption with Time.

shows the variation in average furnace temperature, and the lower one the variation in heat requirements. In the latter diagram, H_1 represents the heat required (B.t.u. per minute) just before the door is opened for a cold charge. As the average temperature of all pieces in the furnace is greatest at that time, radiation to the pieces is the lowest that it is at any time. The doors are all closed, so that there is no loss from them. H_2 is the maximum rate of heat requirement, occurring in the first minute after the door is opened. It includes both heat absorption by the new, cold billet and losses through the

open door. H_{average} represents the average rate of heat transfer to steel and to door losses over the entire daily period of operation of the furnace.

Determination of Maximum Difference between H_2 and H_{average}.—This difference represents the amount of heat which must be supplied by the heat-storage capacity of the furnace in the first part of each cycle, and which is restored to the furnace during the last part, when the heat requirements are less than the average supply. The difference is greatest in the first minute of the cycle. The direct calculation of H_2 and H_{average} is extremely complicated, and of questionable value with the present knowledge of heat transmission, but a fair approximation can be obtained by assuming that:

This assumption is warranted if the shape of the heat-requirement diagram of Fig. 103 is correct.

Since the hot bar removed at the end of each cycle is up to temperature, it is not absorbing heat when removed, so that its removal does not affect the heat requirements in the furnace. The expression $H_2 - H_1$ (net change in heat requirements) then includes only the loss to the open door and the initial radiation to the cold bar.

By the method of the preceding example, the door loss in the first minute after opening is:

$$\frac{1}{60} \times 20 \text{ in.} \times 18 \text{ in.} \times 0.55 \text{ (Table 28)} \times 650 \text{ (Fig. 54)} = 2150 \text{ B.t.u.}$$

From Fig. 82, the surface temperature of an 8-in. diameter bar after one minute of exposure to high heat is about 200 deg., and the average temperature during the first minute is:

$$200 + 70 \qquad 135 \text{ deg. Fahr.}$$

Using 90 per cent of true black-body radiation (see Fig. 54), the heat to the billet in the first minute is:

$$90 \text{ per cent} \times 0.172\left[\left(\frac{2300 + 460}{100}\right)^4 - \left(\frac{595}{100}\right)^4\right]$$

$$\times \cdot \frac{1800 \text{ sq. in., area of billet surface}}{144 \text{ sq. in.} / \text{square foot} \times 60 \text{ min.} / \text{hour}} \qquad 18{,}100 \text{ B.t.u.}$$

The value for $\frac{H_2 - H_1}{2}$, which equals $H_2 - H_{\text{average}}$, is then:

$$2{,}150 + 18{,}100 = 10{,}125 \text{ B.t.u.} / \text{min.}$$

This is the maximum amount of heat which must be obtained in the first minute from a source of heat of such capacity that the removal of that heat will cause a temperature drop of not more than 25 deg.

Sources of Heat: Storage Capacity.—The sources of stored heat in this case are the surface of the hot billets in the furnace and the interior surface of the refractory furnace lining. The depth of the surface strata involved depends upon the rate of penetration of heat, which is dependent upon the diffusivity of the material (see Trinks' *Industrial Furnaces*, Vol. I). Diffusivity of materials is expressed by the term:

$$\frac{\text{Conductivity, B.t.u. / square foot / hour / deg. Fahr. / ft. thickness}}{\text{Specific heat} \times \text{density, pounds / cubic foot}},$$

which is:

$$\frac{34}{0.165 \times 488} = 0.42 \text{ for steel, and}$$

$$\frac{0.75}{0.25 \times 125} = 0.024 \text{ for firebrick.}$$

The thickness of the effective steel strata available for heat storage is, therefore, twenty times that of the firebrick strata.

The volume of effective storing material is the area times the thickness, and the average temperature change is one-half of the change in surface temperature. Since we have assumed an average *surface* drop of temperature in the furnace of 25 deg. in the first minute, the average drop of both steel and firebrick *volume* will be $12\frac{1}{2}$ deg. Fahr.

The change in heat content of any volume of material is the weight times the specific heat per pound times the degrees temperature change. For the above conditions, the heat delivered by the surface strata of the steel in the furnace (12 billets in the furnace) for $12\frac{1}{2}$ deg. temperature drop equals:

150 sq. ft. total area of billets $\times$ $20t$ ft. $\times$ 488 lb. / cu. ft. $\times$ 0.17 specific heat $\times$ $12\frac{1}{2}$ deg. = $3{,}100{,}000t$.

The heat available from the firebrick surface (roof, walls, and hearth), for the same average temperature drop, equals:

332 sq. ft. $\times$ t ft. $\times$ 125 lb. / cu. ft. $\times$ 0.25 specific heat $\times$ $12\frac{1}{2}$ deg. = $130{,}000t$.

The sum of the heat available from steel and brick must equal the additional heat required in the first minute, so that:

$$130{,}000t + 3{,}100{,}000t = 10{,}125 \text{ B.t.u.}$$

From this equation:

$$t = 0.0031 \text{ ft.} = 0.037 \text{ in., penetration into firebrick,}$$

and $20\ t = 0.74$ in., penetration into steel billets.

Comparison of Heat-storage Capacity of 2-ft. High Furnace with 6-ft. Furnace.—From the preceding figures, the heat-storage capacity of the furnace and charge, in B.t.u. per degree temperature change in one minute, is:

$$\begin{array}{lll} \text{Brick:} & 332 \times 0.0031 \times 0.25 \times 125 = & 32 \text{ B.t.u.} \\ \text{Steel:} & 150 \times 0.062 \quad \times 0.17 \times 488 = & \underline{770} \text{ B.t.u.} \\ & & 802 \text{ B.t.u.} \end{array}$$

The additional capacity obtained by adding 4 ft. more to the furnace height can be represented as:

$$(2 \times 4 \text{ ft.} \times 8 \text{ ft.} + 2 \times 4 \text{ ft.} \times 15 \text{ ft.}) \times 0.0031 \text{ ft.} \times 125 \text{ lb./cu. ft.} \times 0.25 \text{ specific heat} = 18 \text{ B.t.u.}$$

The percentage increase in capacity obtained is then:

$$\frac{18}{802} \times 100 = \text{about } 2\tfrac{1}{2} \text{ per cent.}$$

It appears from this analysis that, with ample allowance for the lack of exactness of the method, there is little to be gained by increasing the height of a furnace of the type selected for study. Factors such as the effect of the steel in the furnace of this example are frequently overlooked until a so-called theoretical analysis of a furnace problem is attempted.

Example V: Comparative Fuel Economy of Furnace Arrangements

In the consideration of several furnace arrangements for the same purpose, it is frequently desirable to know the comparative fuel economy, in order to consider that factor in connection with other advantages or disadvantages of the different arrangements. For example, it is sometimes difficult to decide between a direct-fired and a side-fired furnace for a temperature of 2000 deg. Fahr., which is the point of uncertainty in the selection of these two types. For temperatures much below 2000 deg., the advantages of side-firing (temperature and atmosphere uniformity) usually outweigh the disadvantages, and for higher temperatures the limited life of the refractories will usually outweigh the advantages. At 2000 deg., however, the advantages and disadvantages in operation and upkeep often pretty nearly balance, and fuel consumption can be a deciding factor.

In the case of this example, the purpose is to discuss the comparatively simple calculations by which the fuel requirements of two different furnace arrangements can be compared. The furnaces selected for comparison are a direct-fired furnace, such as that shown in Fig. 20 of Chapter III, with flues in the arch, and a side-fired furnace with hearth flues, as shown in Fig. 104. In both cases, the heating chamber is 5 ft. $\times$ 5 ft. $\times$ 2 ft. high, and the firebrick thicknesses are 9 in. for the roof, $13\frac{1}{2}$ in. for the walls, and the same for the doors. No insulation is used. The direct-fired furnace has a solid $13\frac{1}{2}$-in. hearth, and the side-fired furnace a false hearth 12 in. thick. Each furnace is to be lighted at 2 A.M. each morning, charged at 7 A.M., and worked until 5 P.M. In the ten-hour working period 5 tons of steel are heated to 2000 deg. in both cases.

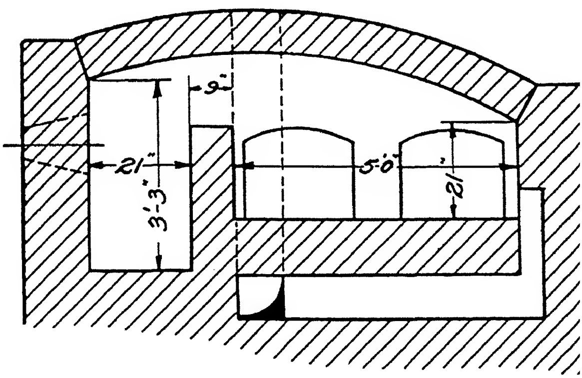


FIG. 104.—Arrangement of a Sidefired Furnace.

A preliminary study of the problem shows that, for the lighting-up period from 2 to 7 A.M., the heat requirements of the direct-fired furnace are absorption by the walls, and may be calculated in the same manner as those of Example 1 in Chapter V. For the working period, the same average rate of absorption plus radiation may be used, and, in addition, there is the heat to the steel and to door losses. The heat requirements of the side-fired furnace for the lighting-up period must include the heat to the brickwork of both the heating and combustion chambers, and also the heat content of the bridgewalls and false hearth. The latter portions are heated from both sides and must be soaked with heat in the lighting period, but since they cool very slowly they may be considered to retain some temperature from the day before. For the working period, the heat requirements consist of heat to all walls and roof, heat conducted through the false hearth, heat to steel, and door losses.

Calculations for Direct-fired Furnace:

							B.t.u.
Heat to steel: 10,000 lb. × 310 (Fig. 50)							=3,100,000
Heat to firebrick:							
	(Table 12)		(Table 13)		Hours		
Roof: 5 ft. × $5\frac{1}{2}$ ft. ×	1400	×	2	×	15		=1,155,000
Sides: 2 × 5 ft. × 2 ft. ×	975	×	3	×	15		= 877,500
Ends: 2 × 5 ft. × 2 ft. ×	975	×	3	×	15		= 877,500
Hearth: 5 ft. × 5 ft. ×	975	×	3	×	15		=1,098,000
							7,108,000
Doors (add 15 per cent of total heat in 15 hours)							=1,070,000
Total heat required in furnace per day							=8,178,000

Calculations for Side-fired Furnace:

In the following calculations it is assumed that the combustion chamber is 200 deg. hotter than the heating chamber, and that the average temperature under the false hearth is 1600 deg.

	B.t.u.
Heat to steel (same as direct-fired):	=3,100,000
Heat to refractories:	
Heating chamber:	
Roof (same as direct-fired)	=1,155,000
Sides (same as direct-fired)	= 877,500
End (one only—same as direct-fired)	= 438,750

False hearth:

$$\frac{9.0 \text{ (conductivity)} \times 25 \text{ sq. ft.} \times 10 \text{ hours} \times (2000 - 1600)}{12 \text{ in. thicknesses}} = 187{,}000$$

5 ft. × 5 ft. × 1 ft. × 125 lb. per cu. ft. × 0.25 (specific heat) × (1800 − 900) = 704,000

Bridgewall: $\frac{3}{4}$ ft. × $1\frac{1}{2}$ ft. × 5 ft. × 125 lb. per cu. ft. × 0.25 × (2100 − 1000) = 193,000

Combustion chamber: (2200 deg.):

	(Table 12)		(Table 13)		Hours	
Roof: 5 ft. × 2 ft. ×	1600	×	2	×	15	= 480,000
Sides: 2 × 2 ft. × $3\frac{1}{4}$ ft. ×	1120	×	3	×	15	= 654,000
End: 5 ft. × $3\frac{1}{4}$ ft. ×	1120	×	3	×	15	= 822,000
18-in. Bottom:						
5 ft. × 2 ft. ×	865	×	4	×	15	= 519,000
Doors: (Same as direct-fired)						=1,070,000
Total heat required in furnace per day						=10,200,250

Comparison of Heat Requirements.—The heat requirements which have been determined for the two types of furnaces have included all of the requirements except the heat lost in the flue gases. This is taken care of by the method of Example 1 in Chapter V, and, for the same oil and the gases leaving the heating chamber at 2000 deg., the available heat in the fuel (heat content—heat in escaping gases) is 67,400 B.t.u. per gal. The daily oil consumption in the two furnaces is then:

$$\frac{8,178,000}{67,400} = 121 \text{ gal.}$$

for the direct-fired furnace, and:

$$\frac{10,200,250}{67,400} \quad 152 \text{ gal.}$$

for the side-fired furnace. Comparison of these figures indicates that the oil consumption is 25.6 per cent greater for the side-fired furnace. This is not a true comparison between the economy of direct-fired and side-fired furnaces, because of the difference in hearth construction in the two cases. A study of the items making up the total heat requirements, however, indicates that the difference between the heat to the solid hearth and the heat absorbed by the false hearth is not great, so that the comparison is nearly right for this case.

It can be seen from the outline of heat requirements that the difference between the two furnaces is greatest for the lighting-up period, because of the difference in the amount of refractory which must be soaked with heat before the furnaces are ready for charging. The overall difference of 25.6 per cent in this case is caused by the comparatively small size of the heating chamber and the large size of the combustion chamber. Much larger heating chambers could be supplied by the same combustion chamber, with consequently lower fuel consumptions. Also, for temperatures as little as 100 deg. lower (1900 deg. or less) in the heating chamber, the combustion chamber could be reduced in size without danger of burning out, and the difference in fuel required, as compared with the direct-fired furnace, would be still further reduced.

This example illustrates the comparatively simple methods by which practical values for fuel consumption may be derived for purposes of comparison, without excessive refinement in the calculations.

Example VI: Salt-bath Furnaces

In the consideration of pot furnaces for salt or lead baths, the determination of the temperature in the combustion chamber around the pot is usually important, and is necessary for estimating fuel consumption or the temperature to which a pot can be satisfactorily heated. The following example is given to show a practical way of quickly determining the maximum temperature difference between the bath and combustion chamber temperature, and also to show the effect of the shape of the pot upon the temperature difference.

Two pots were selected for consideration: one 36 in. long by 12 in. wide, with a depth of 6 in. exposed to the heat of the combustion chamber; and the other 30 in. long by 30 in. wide by 8 in., exposed depth. The problem is to determine the maximum temperature required in the combustion chambers when the pots are operating at full capacity at a temperature of 1500. deg. Fahr. in the bath.

As was stated in Chapter III, the capacity, in pounds of steel heated per hour, of salt-bath furnaces is about one-third of the weight of the salt in the bath. Assuming that the salt used in this case weighs 160 lb. per cu. ft., the production of steel in the first pot will be:

$$\tfrac{1}{3} \times 3 \text{ ft.} \times 1 \text{ ft.} \times \tfrac{1}{2} \text{ ft.} \times 160 = 80 \text{ lb. heated/hour.}$$

From Fig. 50, each pound of steel heated to 1500 deg. Fahr. absorbs 230 B.t.u., so that the total heat to the steel is:

$$80 \times 230 = 18{,}400 \text{ B.t.u./hour.}$$

If we assume that no cover is used over the pot, as is frequently the case, the radiation from the surface of the bath (charcoal or other covering cannot be used, as they can with lead) will be:

36 in. $\times$ 12 in. $\times$ 170 B.t.u./sq. in./hour (from Fig. 54) $=$ 73,500 B.t.u./hour (neglecting emissivity coefficient),

and the total heat required in the pot will be:

$$18{,}400 + 73{,}500 = 91{,}900 \text{ B.t.u./hour.}$$

The pot area exposed to heat is:

$$(2 \times 36 \text{ in.} \times 6 \text{ in.}) + (2 \times 12 \text{ in.} \times 6 \text{ in.}) + (36 \text{ in.} \times 12 \text{ in.}) = 1008 \text{ sq. in.,}$$

so that the heat transfer required will be $\dfrac{91{,}900}{1{,}008} = 91.2$ B.t.u./sq. in./hour.

Neglecting the small drop in temperature through the pot walls, the outside temperature of the pot will be 1500 deg., and black-body radiation (from Fig. 54) at this temperature is 170 B.t.u. per sq. in. per hour. The temperature in the combustion chamber must then correspond to a value of:

$$170 + 91.2 = 261.2 \text{ B.t.u./sq. in./hour in Fig. 54,}$$

which is 1720 deg. Fahr. This is the maximum temperature required, because it considers transfer of heat by radiation only, whereas convection from the gases in the combustion chamber will tend to increase the rate of heat transfer and consequently lower the temperature difference required. For most practical purposes at temperatures over 1400 deg., the values found as above are satisfactorily accurate. At low temperatures, convection is too important to be neglected.

The calculations for the second pot may be made in the same manner, except that allowance must be made for the fact that a pot of this large span must be supported to prevent sagging of the bottom. This is frequently accomplished by means of a large tile which covers the bottom, and in that case the heat transfer to the bottom is almost eliminated. If we assume that only 25 per cent of the area of the bottom is effective, the area of our second pot which is exposed to heat will be:

$$(4 \times 30 \text{ in.} \times 8 \text{ in.}) + (\tfrac{1}{4} \times 900 \text{ sq. in.}) = 1185 \text{ sq. in.}$$

The heat required for the steel is:

$$278 \text{ lb. of steel heated per hour (obtained as before)} \times 230 \text{ B.t.u./lb.} = 64{,}000 \text{ B.t.u. / hour,}$$

and the radiation is:

$$900 \text{ sq. in.} \times 170 \text{ B.t.u./sq. in./hour} = 153{,}000 \text{ B.t.u./hour.}$$

The necessary rate of heat transfer to the pot is then:

$$\frac{64{,}000 + 153{,}000}{1185 \text{ sq. in.}} = 184 \text{ B.t.u./sq. in./hour.}$$

Then:

$$170 \text{ (radiation at 1500 deg.)} + 184 = 354 \text{ B.t.u./sq. in./hour,}$$

and from Fig. 54, the maximum temperature required in the combustion chamber is 1900 deg. Fahr.

The maximum safe working temperature of a pot of any dimensions can be estimated by the foregoing method, if a temperature of about 2000 deg. Fahr. is fixed as the maximum in the combustion chamber. With the usual arrangement of fire-

brick combustion chamber, this is about the maximum temperature that can be maintained without destroying the lining in a short time. The example illustrates the fact that the proportions of the pot constitute an important factor in the temperature required in the combustion chamber surrounding the pot.

EXAMPLE VII: CAPACITY OF FUEL-OIL HEATER

It is sometimes desirable to check the capacity of a fuel-oil heater, used for heating oil in preparation for combustion), and the following example illustrates a practical method of determination for the common form, in which oil is passed through a pipe surrounded by a steam-filled chamber.

The capacity of such a heater depends upon a large number of variables, but these may all be grouped under two principal headings:

1. Heat transfer coefficient—steam to oil.
2. Pressure drop through the heater.

These two limiting factors are interconnected, and one or the other of them limits the capacity. The heater must be so designed that the necessary quantity of oil can be heated to the desired temperature, and also that the pressure drop will not exceed a set figure, 35 lb. per sq. in. being the practical limit in most cases.

Suppose that an oil heater has a heating surface of 8.0 sq. ft., which is the surface area of a pipe coil made of 33 ft. of standard $\frac{3}{4}$-in. pipe (0.53 sq. in. inside area). The steam pressure is 125 lb. per sq. in., and the temperature of the oil entering the heater is 70 deg. The capacity of the heater is to be 200 gal. of oil. The problem is to determine the final temperature of the oil leaving the heater, and whether the heater will satisfactorily handle this quantity of oil.

The coefficient of heat transfer in a heater of this kind varies from about 20 to 40 B.t.u. per sq. ft. per deg. Fahr. per hour for oil velocities of 1 to 4 ft. per sec. In this case, the velocity in the pipe is:

$$\frac{200 \text{ gal./hour} \times 231 \text{ cu. in./gal.}}{3600 \text{ sec./hour} \times 12 \text{ in./ft.} \times 0.53 \text{ sq. in.}} \quad 2.02 \text{ ft./sec.,}$$

and the coefficient is about 24 B.t.u. per sq. ft. per deg. Fahr. per hour. The heat transfer per hour is then:

$$8 \text{ sq. ft.} \times 24 \times \left(350 - \frac{70 + T}{2}\right) = 192 \left(350 - \right.$$

where 350 is the temperature of saturated steam at 125 lb. per sq. in. pressure, and T is the final temperature of the oil.

The heat absorbed by the oil is:

200 gal./hour $\times$ 7.8 lb./gal. $\times$ 0.50 (specific heat) $\times$ $(T - 70) = 780$ $(T - 70)$.

Equating these two expressions:

$$192 \left(350 - \frac{70 +}{} \qquad = 780\ (T - 70),\right.$$

and $T = 166$ deg. Fahr., final oil temperature.

The pressure drop can be calculated by the formula:

$$P = fLs\frac{Q^2}{D^5}$$

which is discussed in Chapter VII. If the oil is of 20 Bé. gravity and 0.93 specific gravity, the Saybolt viscosity for an average temperature of $\frac{70 + 166}{2} = 118$ deg. Fahr. will be about 330 sec. (see Chapter II). Then, referring to discussion given in Chapter VII, the term

$$\frac{Qs}{D \times \text{Saybolt viscosity}} = \frac{3.33 \text{ gal./min.} \times 0.93}{0.82 \text{ in.} \times 330} = 0.0115.$$

For this value, $1000f$ = about 5.0, and

$$P = \frac{5}{1000} \times 33 \text{ ft.} \times 0.93 \times \frac{(3.33)^2}{(0.82)^5} = 4.62 \text{ lb./sq. in. pressure drop.}$$

This is well within the allowable limit of 35 lb. per sq. in.

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